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ANALYSIS OF VFR CLOUD CLEARANCE AND VISIBILITY STANDARDS

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ROWLAND & COMPANY, INC.

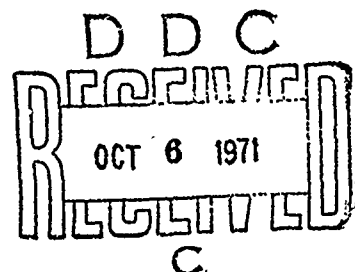
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16. Abstract <p>  A three-dimensional vector analysis of a two-aircraft near-miss geometry was developed and used to generate a numerical safety rating scheme for quantifying the degree of hazard associated with aircraft-to-cloud separation minimums and with speed-visibility restrictions. Hazard functions were generated for low, medium, and high-speed aircraft. Based upon the resulting data, proposed new Visual Flight Rules were created. The rationale behind the new rules is discussed. Possible effects of the rules are noted. Numerous inadequacies of the data which was inserted in the limited mathematical model are indicated. Additional research needs are sketched. Concern over the broad impact of the proposed new VFR rules, coupled with reservations about the limited scope of the study and the paucity of hard data to incorporate into and actually test out the validity of the model, cause the authors to suggest the firm necessity of substantial additional technical investigation and broad discussion prior to adoption of the new rules. </p>					
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The Federal Aviation Administration is responsible for the promotion, regulation and safety of civil aviation and for the development and operation of a common system of air navigation and air traffic control facilities which provides for the safe and efficient use of airspace by both civil and military aircraft.

FOREWORD

Acknowledgement is extended to Mr. Frank Staiano and Mr. Carmen Munafo of the Computer Applications Section, Systems and Applications Branch, National Aviation Facilities Experimental Center (NAFEC), for their assistance in running the computational aspects of the program. We have also appreciated the series of technical discussions provided by Messrs. Robert Buck, John Brennan, and John Reed of the Federal Aviation Administration Detection Systems Branch, Washington, D.C.

As has been the case throughout this entire research project, the joint guidance and support continually provided by Mr. Paul Rich and Mr. Roman Spangler, who have been the technical monitors of this project from NAFEC, has been simply outstanding. Their degree of understanding of what we were attempting to do enabled them to constructively criticize and guide our efforts. Their perseverance and persistence in getting us access to the technical assistance of the Federal Aviation Administration computational facilities was of great value. Above all, their steadfast advocacy of the rational, experimental, mathematical, empirical technical approach to rule-making, which we have followed, is clearly in the best tradition of sound systems engineering practice and deserves special notice and commendation. Their encouragement and strength has been of such nature that it has seemingly emboldened us to make a frontal assault on a very hostile fortress while only clad in lightweight armor and carrying a slingshot. One must agree that the ability to get a research contractor to do that is a demonstration of real leadership on the part of the technical monitor.

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SECTION I. INTRODUCTION

The majority of flying hours are conducted under Visual Flight Rules (VFR) in which the essential technique of avoiding collisions between aircraft is for their respective pilots to visually watch for and detect each other and then maneuver their aircraft so as to avoid each other. This has been characterized as the "see-and-avoid" doctrine, or the "see-and-be-seen" doctrine. To facilitate the operation of this concept rules have been promulgated that permit pilots to fly by visual reference to the ground with certain proscribed visibility requirements and with certain separations being maintained horizontally and vertically from clouds:

BASIC VFR WEATHER MINIMUMS

- (a) Distance from clouds. Except as provided in 91.107*, no person may operate an aircraft under VFR--
 - (1) Within the continental control area at a distance less than 1,000 feet vertically and one statute mile horizontally from any cloud formation;
 - (2) Within any other controlled airspace at a distance less than 500 feet below or 1,000 feet above, and 2,000 feet horizontally from, any cloud formation;
 - (3) Within a control zone, beneath the ceiling when the ceiling is less than 1,000 feet;
 - (4) Outside controlled airspace at an altitude of more than 1,200 feet above the surface, at a distance less than 500 feet below or 1,000 feet above, and 2,000 feet horizontally from, any cloud formation; or
 - (5) Outside controlled airspace at an altitude of 1,200 feet or less above the surface, unless the aircraft is clear of clouds.
- (b) Flight visibility. Except as provided in 91.107*, no person may operate an aircraft under VFR--
 - (1) In the continental control area unless flight visibility is at least five statute miles;
 - (2) In any other controlled airspace unless flight visibility is at least three statute miles; or
 - (3) Outside controlled airspace, unless flight visibility is at least one statute mile.
However, subparagraph (3) of this paragraph does not apply to the operation of a helicopter at or below 1,200 feet above the surface at a speed that allows the pilot adequate opportunity to see any air traffic or other obstruction in time to avoid a collision.
- (c) Ground visibility. Except as provided in 91.107*, no person may takeoff or land an aircraft, or enter the traffic pattern of an airport, under VFR, within a control zone -
 - (1) Unless ground visibility at that airport is at least 3 statute miles; or

*91.107 of U.S. Federal Aviation Regulations

- (2) If ground visibility is not reported at that airport, unless flight visibility during landing, or takeoff, or while operating in the traffic pattern, is at least 3 statute miles.
- (d) For the purposes of this section, an aircraft operated in accordance with 91.109* at the base altitude of a transition area, a control area, or the continental control area, is considered to be within the airspace directly below that area.

These requirements have been based upon the general appreciation of the fact that a pilot needs some minimum amount of time to detect the presence of, and maneuver away from, another aircraft which has just loomed out of the haze, come around from behind a cloud, or come up or down at him out of a cloud layer. All things considered, the concept works surprisingly well.

Nonetheless, each year there are a number of midair collisions and near-misses on days with VFR weather so, obviously, the concept is not working as well as it might. (3 through 11) One suspicion is that the pilots may not have a sufficient amount of time to see and avoid each other. This lack of time can come about due to several different causes:

1. Visibility too limited for contemporary operations--
The VFR flight rules were formulated many years ago. Since they went into effect there have been literally enormous changes in aircraft speeds. Hence, where 1 mile horizontal visibility used to mean 20 to 30 seconds of time for detection, it may now mean only 3 to 5 seconds for two opposing jets. The possibility exists that aviation needs a new horizontal visibility rule for VFR such that we would go back toward a more realistic detection and avoidance opportunity.
2. Horizontal separation from clouds -
With a heavy increase in the number of aircraft in operation and with those aircraft being generally better equipped with navigational equipment for long range work, there is a pronounced increase in the amount of traffic going up and down through breaks in the overcast or through the open areas between scattered clouds in order to get to and from "VFR On Top" operations. Additionally, there is an increasing amount of Instrument Flight Rule (IFR) traffic so Air Traffic Control (ATC) has to make more and more use of altitudes which are at cloud level so that many more aircraft are operating on IFR flight plans but, in reality, are operating in and out of cloud. There is, therefore, an increasingly good chance for mixed IFR/VFR traffic to encounter one another in the clear spaces between clouds. There is also the simple opportunity for another VFR aircraft to suddenly pop out from behind a scattered cloud and, since there are more aircraft in the skies these days, the opportunity for such a sudden encounter is materially increased.

Obviously, one potential answer to this portion of the collision problem would be to require that pilots stay further away from clouds. In this way one would have to circle more widely around a cloud in a

*91.109 of U.S. Federal Aviation Regulations

horizontal plane and would have more reaction time against some other pilot circling around the same cloud in the opposite direction. Similarly, the IFR pilot operating "in-and-out" would have enough time to inspect the area through which he is to pass while he is "in the clear" between clouds. At the same time, the legally VFR pilot operating in the clear between clouds would have time enough to detect an IFR flight which had just popped out of cloud into his clear space.

It is quite obvious that if the clear area between clouds is large enough, everyone described above would have sufficient time to get away from each other. It is also immediately evident that, if these space requirements were very large, the separations between clouds would have to be large. In turn, this would mean a limitation on the number of opportunities for aviators to go up or down between clouds to VFR conditions on top or to VFR below scattered or broken clouds. It could also mean mixed VFR/IFR traffic at cloud level would be practically impossible. Such an outcome would possibly constitute a substantial impediment to the flow of traffic. Viewed over-all, the imposition of a much more stringent rule on horizontal separation from cloud could result in a severe restriction upon VFR operations. This, in all probability, would hit the General Aviation segment of the flying community far and away the hardest blow. Depending upon the stringency of the rule invoked it just could mean that VFR operations would have to stay below cloud bases even on days when the clouds are scattered as much as a couple of miles apart. In essence, that much separation between clouds would almost never occur on summer altocumulus days so it could result in a terrific compression of all the VFR traffic into one thick scramble down beneath an otherwise essentially empty sky. That mere outcome alone could increase the chances of collisions by enough to warrant a return to less stringent cloud separation rules. One might find it a better over-all risk to take his chances on collisions around the vicinity of the clouds in order to escape the crowded conditions down beneath.

3. Vertical separation -

In earlier times, when VFR rules were last written, performance capabilities of aircraft were markedly inferior to those of the present. This is certainly the case with rates of climb and descent. Whereas 1,000 to 2,000 feet-per-minute climbs or descents were once quite good nowadays rates of 4,000 to 6,000 feet-per-minute are common and higher rates are encountered, especially in military aircraft. The net result is that an aircraft can pop up out of an undercast or drop down out of an overcast and become at co-altitude with another aircraft which has been operating with legal, but suddenly very inadequate, vertical separation. One apparent solution could be to require VFR aircraft to maintain greater vertical separation from clouds. This would give an extra cushion of time to detect and avoid each other. However, one can immediately see that this can conceivably be very hard on low performance, low equipment aircraft such as the majority of General Aviation. For example, any rule requiring over 1,000 feet vertical separation below cloud base would mean a VFR flight could not legally fly over a city which had a 2,000-foot ceiling in effect at the time.

Unequipped aircraft would have difficulty operating on top of a cloud layer even at 10,000 or so if they were driven up another couple of thousand feet by a "1,000-foot altitude above cloud" rule plus a "direction of flight" rule. For example, assume cloud tops at 10,600 feet, the pilot must maintain 1,000 feet separation so must fly at 11,600 feet but if his direction of flight is north-easterly VFR, he must maintain an odd altitude plus 500 feet and must go on up to 13,500 feet which is oxygen altitude, particularly at night. This kind of rule would obviously ground a substantial number of flights by forcing them either too high or too low.

Note that our discussion has only assumed the rule to be a 1,000-foot vertical separation from cloud and note that, even though it can be seen to cause great havoc to air operations, it did not really give much protection since at fairly routine rates of climb or descent the prior search time is measured only in very few seconds for the respective pilots. To give them a truly comfortable time interval, especially with high performance aircraft, would require a greater separation and that would only make operating restrictions even less acceptable.

Viewed over-all, the penalties of having more restrictions must be weighed against the increase in safety which would result from maintaining greater separation of aircraft from clouds and greater horizontal visibility. It is understood that almost any recommendation made for a change in these rules may immediately provoke partisan activity one way or another. The intention, therefore, is not so much to avoid controversy as it is to provide the advocates with some good data around which to center their arguments. Accordingly, an attempt is made to provide realistic assumptions, reasonably realistic situations have been set up, the data have been run carefully, all of the data have been presented and, at the conclusion of everything, a specific set of rules has been proposed. Any better set of ideas will be welcomed into the arena. At least this report presents something specific to be discussed knowledgeably instead of opinionated arguments unsubstantiated by data.

SECTION II. BACKGROUND

The majority of aviation operations are conducted under VFR rules with aviators maintaining separation by direct visual techniques. The present analysis of visual separation techniques focuses on the doctrine of "See and Avoid." An in-depth study into this doctrine has been prompted by the undeniably large number of midair collisions and near midair collisions that have occurred under VFR conditions and which have been attributed to the "Pilot's failure to see and avoid other aircraft." (3 through 11)

The two basic tenets of the "See and Avoid" doctrine are: first, the VFR pilot must maintain an adequate outside-the-cockpit visual search for other aircraft; and second, all planes flying VFR must insure their visibility by flying clear of all clouds, as required by regulation, and using approved exterior lighting systems. In this report both aspects of this doctrine will be analyzed with respect to the separation distance between VFR aircraft and clouds and with respect to minimum visibility conditions. In two-aircraft encounters, both aircraft share the responsibility to see and avoid, to see and be seen. *The following analysis assumes both pilots in an encounter are adhering to the tenets of this doctrine, are actively searching the field of view, and will make appropriate avoidance maneuvers when and as needed.* This being the case, the objective of this analysis is to reasonably guarantee the pilots sufficient reaction time to respond to a situation in which one aircraft suddenly becomes visible.

This particular area of study epitomizes one of the weak points of the "See and Avoid" doctrine--the interfacing of VFR and IFR traffic. While the VFR pilots rely on their eyes alone to detect other traffic, the IFR pilots quite frequently rely solely on an overburdened ATC system as substitute eyes. The ATC system is often blind to VFR traffic. For this reason the pilot on a VFR clearance must remain clear of all clouds to allow himself to be seen by other VFR traffic, but he must also allow himself sufficient cloud clearance in order to react to an IFR flight emerging suddenly from the cloud boundary since the IFR pilot has no guaranteed way to know of the VFR pilot's existence. This sad situation emphasizes the need for a sharing of responsibility and alertness on the part of both VFR and IFR traffic in mixed conditions.

A recent mathematical analysis of the lateral cloud clearance standards (19) has questioned the adequacy of current standards on just this basis. The question to be answered is "do the current standards allow adequate pilot/aircraft reaction time to insure safe passage when an IFR flight emerges from a cloud boundary layer in the vicinity of a VFR flight; and, if so, what margins of safety exist to cover pilot errors and minor infractions of the regulations?"

From a pragmatic viewpoint, a survey of accident statistics conducted by ROWLAND & COMPANY as part of the present contract has failed to indicate that aircraft breaking through or out of cloud boundaries were a significant cause/factor in the numerous actual midair collisions that occurred in the past 20 years. This can be interpreted either as the fact that such collisions did not occur due to this cause, or if they did, this factor failed to enter the accident report. On the other hand, in the recent near midair collision study (15)

76 near misses or related incidents were reported involving aircraft breaking through clouds. Forty-four of these incidents were considered hazardous. One should bear in mind that these reported incidents probably reflect only a fraction of the actual number of incidents that may have occurred. It would seem that the sudden appearance of aircraft in the vicinity of clouds may be a serious affair.

Statistical studies often shed little light on the mechanistic nature of a problem apart from calling attention to the existence of trouble and giving a general idea of the extent of the problem. While perhaps not scientifically precise, the subjective comments of individuals who have been involved in such incidents as described above, prove exceptionally informative and definitely unveil the problem as the pilots see it. Several selected pilot comments taken from an admittedly old, but probably useful, CAB report (2) are quoted below to serve as a general overview of this hazardous problem.

"A DC-6 missed a Luscombe by 100 feet while making an approach to land at 1,400 feet. Cockpit visibility 1 mile; 400 feet below overcast. Pilot suggests keeping light planes out of the air when the visibility is less than 3 miles around large airports."

"An airline pilot came within 500 feet of another air carrier aircraft at 2,000 in marginal VFR weather. He stated the other pilot was attempting to hold VFR in marginal conditions and suggests IFR control within 20 miles of any commercial airport when visibility is less than 5 miles."

"A scheduled air carrier pilot, making an ILS landing at an uncontrolled airport, reported sighting a single-engine aircraft 200 feet distant as he broke out of clouds at 400 feet."

"Making ILS approach in and out of cumulus--broke out of one cloud--light plane crossed 200 feet above us. Checked with tower and light plane did not have IFR clearance."

"We were climbing to 4,000 in holding pattern--other aircraft was VFR ON TOP. He was only about 100-200 feet above overcast."

"While on IFR clearance to 500 ON TOP, on breaking through, other aircraft was cruising in tops of overcast. ATC had no information on other aircraft."

"While making ILS approach, just broke out underneath the overcast and observed a Cessna on the localizer about 300 feet below the clouds. It was not making an approach, just flying around."

"We were just breaking out of overcast inbound on ILS--other aircraft outbound. Reciprocal heading within 100 feet of overcast."

"Making range approach--just broke out over range station and sighted light aircraft 100 feet or less to the left flying in and out of ragged overcast."

From these comments several observations can be made:

1. In most of the reported instances one aircraft was making an altitude change upward or downward through cloud and encountered another aircraft which was in level cruise slightly above or below the cloud layer.
2. Some instances are reported in which an aircraft breaks into the clear space between clouds and encounters another aircraft also cruising nearby to cloud.
3. Practically no time was available for either pilot to make a planned, rational avoidance maneuver. In most cases, the planes simply missed each other by chance alone.
4. The "other aircraft" was generally faulted mainly for flying too close above or below clouds while it was ostensibly on a VFR clearance, (usually it was said to be illegally close). While precise measurements are rare and opinions probably emotionally weighted, the facts seem quite clear.

Since little is known of the effect the stresses of a near miss have on a pilot's speed-distance judgments the above comments are certainly subject to debate. The actual separation between the VFR aircraft and cloud boundary in the incidents reported above may, or may not, have been precisely as reported. The unanimity of the reporting pilots would suggest, however, that the VFR aircraft was most often likely to have been at fault. In separating the facts from opinions, however, the fact remains that one aircraft did unexpectedly emerge from a cloud boundary in close enough proximity to another aircraft that the incident was of sufficient concern to the pilots involved that a report was filed on the incident. So, even if it was sufficiently good separation to be actually "legal," it was still regarded as too close.

The increasing popularity of VFR General Aviation, the growing amount of IFR General Aviation traffic, and the growing demand for increased commercial passenger service will undoubtedly lead to a much greater mixing of IFR-VFR traffic. Since "breakout of clouds" is listed as a hazardous problem area in the mixing of IFR and VFR traffic (15) the entire problem area merits careful investigation with an eye toward possible rule changes as a preventive measure to insure safe skyways in the future.

As part of the research this significant topic requires, the study contained in this report presents a mathematical analysis of the outcome of operating with various aircraft-to-cloud separation limits and develops a methodology for computing the degree of hazard associated with adoption of a given separation standard. Selecting scenarios typical of VFR-IFR traffic mix, a set of recommended aircraft-to-cloud separation limits are proposed as well as a set of safe speed-visibility relations. *It is to be clearly understood by the reader that the recommendations made herein are based solely on a theoretical mathematical approach using linear, non-accelerating flight paths, and that the actual standards that may ultimately be adopted should reflect additional safety factors to account for pilot judgment errors, economic considerations, degree of restriction upon freedom to fly, etc. In view of the*

paucity of human factors data, weather data, and economic model data available to apply to this area, the recommended standards in this report should be regarded as representing the best estimates possible at this time and merely as the stimulus to further research, analysis, and discussion.

SECTION III. MATHEMATICAL ANALYSIS

Previous analyses of the near-miss geometry as applied to cloud separation standards (19) on the collision problem in general (16, 18) are based almost entirely on a two-dimensional, linear collision geometry, primarily in the horizontal plane. Actual pilot statements (2), however, indicate that most near misses involving exit from cloud occur in the vertical plane, that is, while one of the other aircraft is climbing or descending through a cloud layer. Thus, while the near miss on the horizontal plane (two-dimensional) lends itself to a conveniently simplified geometrical analysis, the more complicated *three-dimensional* near miss actually lies more nearly at the heart of the cloud separation problem and is, therefore, the issue to which attention will be addressed herein.

Inferences drawn from the previous geometrical analyses in the horizontal plane cannot always be translated into the vertical situation with validity for several reasons. One major objection is the fact that, as opposed to the simple horizontal plane collision situation, a near miss need not necessarily lie in a plane formed by the intersection of the flight path trajectories of the two aircraft; that is, the flight paths of the two aircraft involved need not actually intersect as is the case in a horizontal co-altitude near miss or collision. Therefore, two-dimensional analyses of the kinds which have been done to date present only a limited number of the near miss geometries possible under what is actually a three-dimensional problem.

A second objection to simply rotating the axes of horizontal collision analyses and then translating the conclusions into vertical situations is the fact that the flight path angle, Γ , of ascending and descending aircraft is limited by power considerations, passenger acceptance, pilot concern over loss of visibility in very nose-high attitudes, etc. The maximum angles used in practice appear to be approximately 10° while the average value is 5° (17). This condition imposes restrictions on the relative angle between the tracks of two aircraft as a function of their relative positions. Thus, any statements generated by a horizontal analysis that are founded on the proposition that all relative bearing angles are equally probable or possible for any given relative position, lose their validity when extrapolated into vertical situations.

The general approach taken by ROWLAND & COMPANY herein is to consider the three-dimensional near miss geometry from the start and to formulate the analysis methodology in terms of three-dimensional vector equations. In this way a more true picture of the pilot's environment is studied. In actual operations, not only do aircraft approach from every side in a horizontal plane but, in reality, the pilot must constantly concern himself with other aircraft descending or climbing in the vicinity of airport or airway traffic, or possibly coming up or down at him out of cloud. In fact, an altitude change on the part of one of the aircraft has been shown to be typically the case in the majority of cloud-related incidents reported. There appear to be fewer cases of aircraft popping out of the sides of clouds. Since it is recognized from the start that the pilot flies in a three-dimensional world, it must also be true that an analytic study of the pilot's world must find its mathematical basis in a three-dimensional conception of the pilot's world.

To simplify matters at the start, two unaccelerated aircraft trajectories are assumed in the analysis. The test imposed on these trajectories is whether or not they lead to a near miss situation in a less than acceptable period of time. Using one of the aircraft as a reference the probability of hazardous trajectories occurring from a randomly flying "other" aircraft is computed for the space surrounding the reference aircraft. Integration of this probability function on geometric planes representing cloud boundaries then indicates the relative degree of hazard of flying within a given distance of a cloud boundary. The particulars of this analysis are as follows.

Two aircraft are considered. The first, designated as the reference aircraft, is assumed to fly straight and level in non-accelerated flight at some certain distance above or below a cloud layer. The heading of the reference aircraft defines the x-axis of the Cartesian coordinate system in which the analysis is carried out. The z-axis is perpendicular to the horizontal plane (Figure 1). The second aircraft in the analysis, designated as the emerging aircraft, is made to appear precisely on the cloud boundary layer in linear, non-accelerated flight at the instantaneous start of the analysis, and is attributed to be either climbing or descending at a certain constant rate, whichever the case may be.

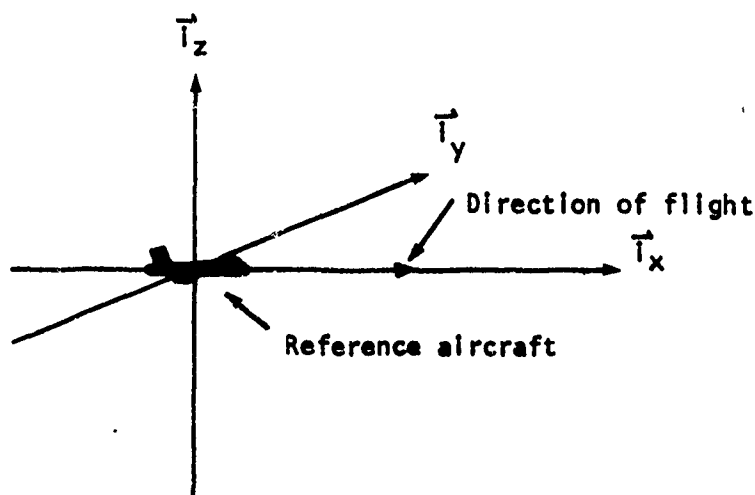


Figure 1. Analysis Reference Coordinates

The formulation of the geometrical equations of a near miss is based on a vector analysis of the near miss geometry. Four-position vectors are required to construct a near miss. Vector $\vec{V}_1(t)$ defines the projected position of the reference aircraft at some future time, t . The direction of $\vec{V}_1(t)$ also defines the x-axis of the coordinate system used in the analysis. For convenience in this analysis the reference aircraft is always assumed to be flying parallel to the horizontal plane of the earth, as well as the plane defined by either bases or tops of clouds. The magnitude of $\vec{V}_1(t)$ is simply $v_1(t)$ where v_1 is the velocity of the reference aircraft (Figure 2).

The plane defined by either bases or tops of clouds is also assumed to be horizontal in terms of the coordinate system defined above. The magnitude of

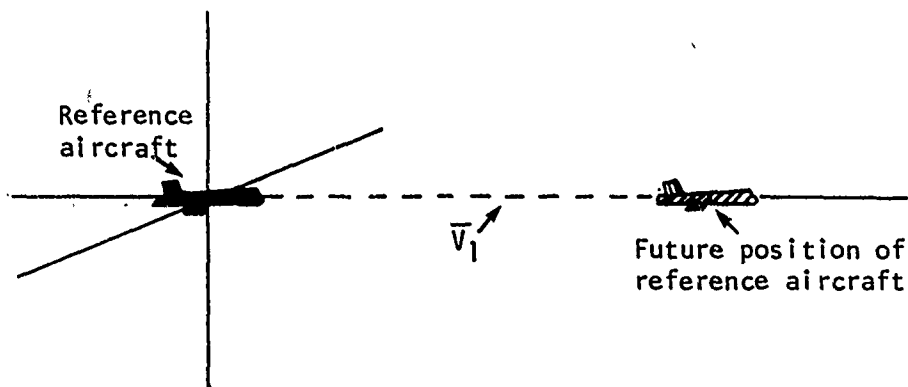


Figure 2. Projected Trajectory of Reference Aircraft: Vector \vec{V}_1

$\vec{V}_1(t)$ is simply $v_1 \cdot t$, where v_1 is the velocity of the reference aircraft (Figure 2) and t is the time from the start of the trajectories. The unit vector \vec{i}_x is in the x direction.

$$(1) \quad \vec{V}_1(t) = (v_1 \cdot t) \vec{i}_x$$

Understanding of the analysis is facilitated by the conception of a hypothetical sphere which surrounds and moves with the reference aircraft. This sphere is called the "near miss sphere." It is the simplest geometrical shape that can be used to define a near miss. \vec{V}_2 is defined by a point on the near miss sphere and the position of the reference aircraft. (As will be detailed below, one of the conditions for achievement of a near miss is that the emerging aircraft touch or enter this sphere from any direction at some time.) The magnitude of \vec{V}_2 is the near miss distance M and its direction is defined by the azimuth and elevation angles θ and ϕ respectively, directing the vector to the point on the near miss sphere at which the emerging aircraft intersects the sphere (Figure 3).

$$(2) \quad \vec{V}_2 = M \cos \phi \cos \theta \vec{i}_x + M \cos \phi \sin \theta \vec{i}_y + M \sin \phi \vec{i}_z$$

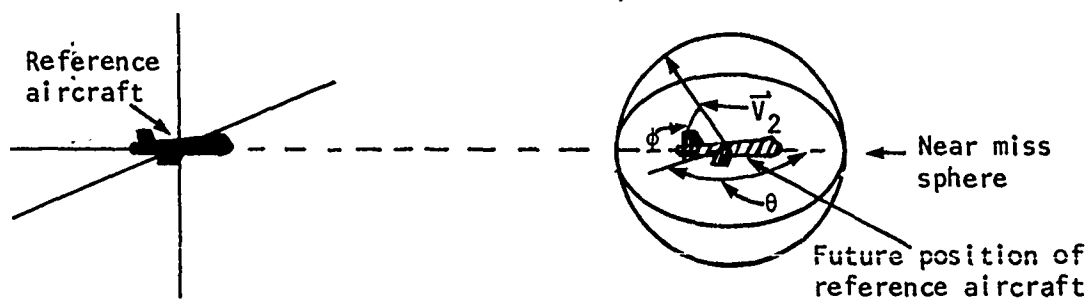


Figure 3. Near Miss Sphere: Vector \vec{V}_2

All azimuth angles in this analysis are defined positive in the clockwise sense when viewed from above the horizontal plane; likewise, all elevation angles rotating upwards from the horizontal plane are positive. The unit vectors \vec{i}_x , \vec{i}_y , and \vec{i}_z are in the x, y, and z direction respectively.

Two additional vectors are required to specify the projected position of the emerging aircraft. \vec{V}_3 is the initial position of the emerging aircraft. It locates the initial position of the emerging aircraft (i.e., at the time it emerges from a cloud surface or, in other words, $t = 0$) with respect to the origin of the coordinate system (the initial position of the reference aircraft). It is defined by the position triplet (ϵ , δ , R) where ϵ is the elevation angle of the emerging aircraft with respect to the reference aircraft; δ , the relative bearing angle; and R , the slant range (Figure 4). For example, in Figure 4 the emerging aircraft appears above and directly to port of the reference aircraft at the instant of emergence.

$$(3) \quad \vec{V}_3 = R \cos \epsilon \cos \delta \vec{i}_x + R \cos \epsilon \sin \delta \vec{i}_z + R \sin \epsilon \vec{i}_y$$

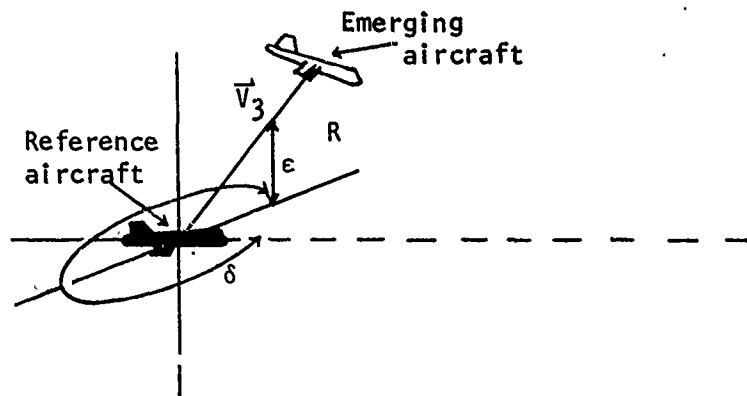


Figure 4. Initial Position of Emerging Aircraft: Vector \vec{V}_3

The projected trajectory of the emerging aircraft with respect to its initial position is defined by $\vec{V}_4(t)$. The magnitude of $\vec{V}_4(t)$ is $k v_1 t$ where k is the ratio of emerging aircraft airspeed to reference aircraft airspeed, v_1 is the velocity of the reference aircraft, and t is time. The direction of $\vec{V}_4(t)$ is defined by the relative heading and flight path angles, ψ and Γ respectively (Figure 5).

By the convention established above, a descending aircraft has a negative flight path angle, $-\Gamma$.

$$(4) \quad \vec{V}_4(t) = k v_1 t \cos \Gamma \cos \psi \vec{i}_x + k v_1 t \cos \Gamma \sin \psi \vec{i}_z + k v_1 t \sin \Gamma \vec{i}_y$$

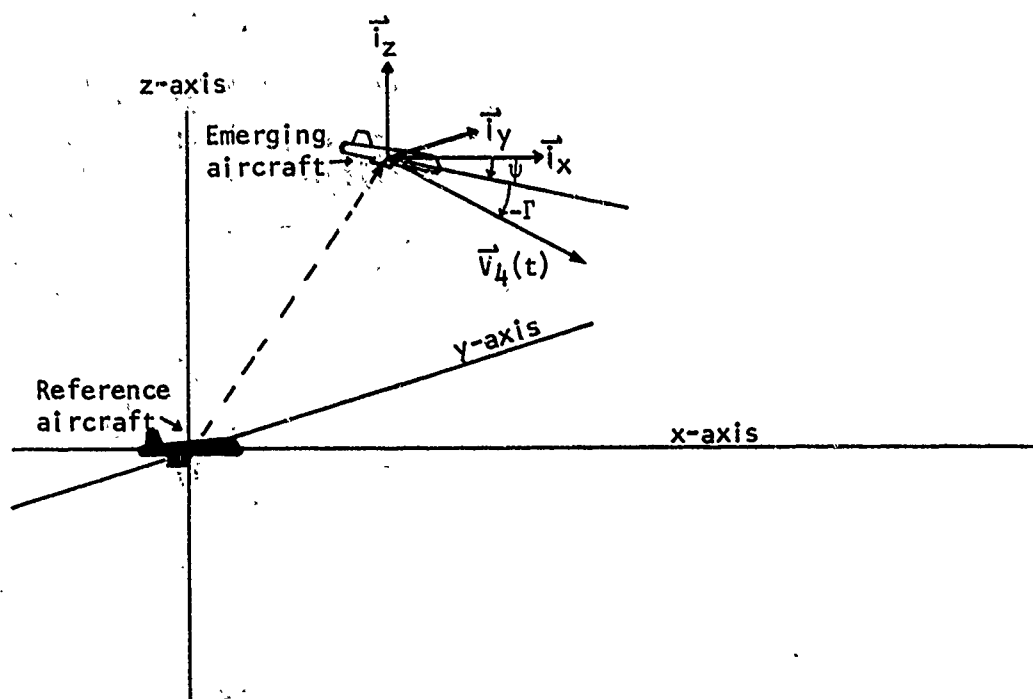


Figure 5. Projected Trajectory of Emerging Aircraft: Vector \vec{V}_4

The summation $\vec{V}_3 + \vec{V}_4(t)$ defines the instantaneous position of the emerging aircraft at time t with respect to the initial position of the reference aircraft.

Defining a near miss to be the case in which the emerging aircraft touches or penetrates the reference aircraft's near miss sphere from any direction at some future time, then the vector equation which must hold at the time the near miss occurs is:

$$(5) \quad \vec{V}_1(t) + \vec{V}_2 = \vec{V}_3 + \vec{V}_4(t) \text{ for } t > 0 \text{ and } R > M$$

The two constraints $t > 0$ and $R > M$ clarify the mathematical statement and exclude solution to equation (5) that would imply that the near miss had already occurred before the start of the problem ($t < 0$) or that near miss conditions exist at the start of the problem ($R < M$). As will be seen later, the case of a near miss existing at the start of the problem is mechanically accounted for in the computer analysis. Equation (5) states the necessary and sufficient conditions for a near miss to occur; no other conditions (such as penetration of the horizontal reference plane) are intended or implied.

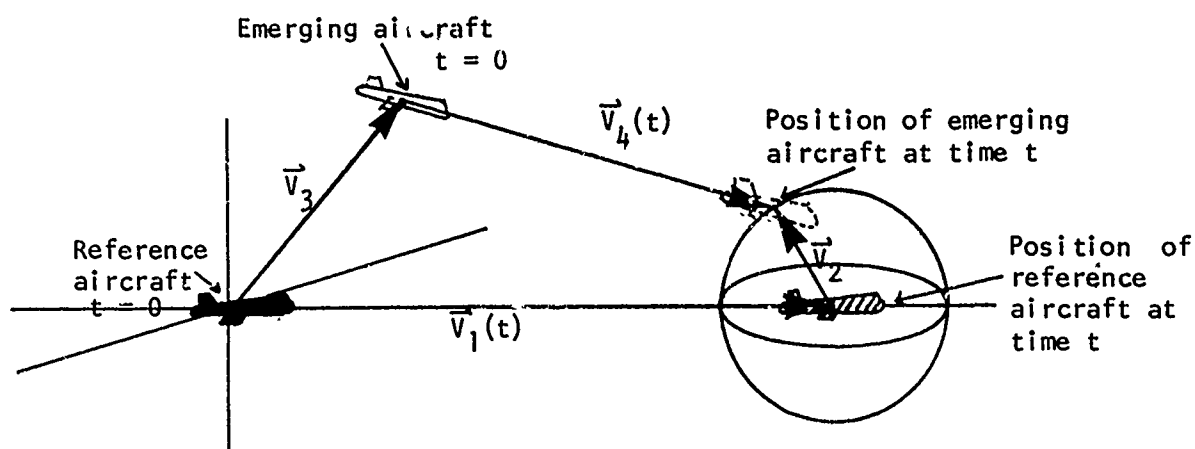


Figure 6. Vector Relationships for a Near Miss

There are three independent scalar equations in equation (5) corresponding to the three orthogonal axes of the coordinate system:

$$(6) \quad \vec{i}_x: v_1 t + M \cos \phi \cos \theta = k v_1 t \cos \Gamma \cos \psi + R \cos \epsilon \cos \delta$$

$$(7) \quad \vec{i}_y: M \cos \phi \sin \theta = k v_1 t \cos \Gamma \sin \psi + R \cos \epsilon \sin \delta$$

$$(8) \quad \vec{i}_z: M \sin \phi = k v_1 t \sin \Gamma + R \sin \epsilon$$

In the equations above, M is size of the near miss distance in feet and R is the initial slant range to the emerging aircraft, in feet; v_1 is in feet per second. Dividing these equations by v_1 to produce the new parameters

$m = \frac{M}{v_1}$ and $r = \frac{R}{v_1}$ and eliminating the variables ϕ and θ by substituting equations (7) and (8) in equation (6), the following relation among the remaining seven parameters holds:

$$(9) \quad \left(1 + k^2 - 2k \cos \Gamma \cos \psi \right) t^2 + \left(2r \left((k \cos \Gamma \cos [\psi - \delta] - \cos \delta) \cos \epsilon + k \sin \Gamma \sin \epsilon \right) \right) t + (r^2 - m^2) = 0$$

The units of the new parameters m (miss distance in seconds) and r (range in seconds) are seconds of time. Dividing the equation through by v_1 devoids the solutions of a direct reference to reference aircraft velocity; thus, in a sense, generalizing the solutions. The parameters m and r , expressed in seconds, can be readily converted to specific distances M and R for a particular situation by multiplying by the corresponding value of v_1 .

The roots of equation (9) represent the times at which the projected path of the emerging aircraft intersects the projected location of the near miss sphere surrounding the reference aircraft. Non-real roots of equation (9) imply that this intersection never takes place while negative real roots indicate that the intersection has already taken place in the past. Thus, only those combinations of parameters which lead to positive real solutions of equation (9) are of interest here.

The prediction of a near miss using the roots of equation (9) assumes, of course, that both aircraft maintain their present trajectories. In actual situations in which the aircraft are visible to each other each pilot, having detected a threatening aircraft, will most likely maneuver his own aircraft in the way he thinks will be best to avoid the other aircraft and, hopefully, to avoid a near miss or a crash. In order for this to occur, however, the pilot needs sufficient time to detect, evaluate, and successfully maneuver his aircraft. The total time required for these activities is lumped together in this analysis and arbitrarily defined as the pilot's critical reaction time, T .

The concept of reaction time is particularly well suited here since it usually characterizes a subject's response to the sudden appearance of a stimulus. In this case the emerging aircraft, the stimulus, is assumed to be hidden from view either by clouds or reduced horizontal visibility conditions until a given time, at which point it becomes available for visibility to the pilot of the reference aircraft, (although, of course, the pilot does not necessarily see it at that instant or, for that matter in this mathematical analysis, he may never see it). This point in time is defined as the starting time of the problem, i.e., $t=0$.

Equation (9) projects the trajectories of the two aircraft using their respective headings and velocities and locations at $t=0$. This projection determines, first of all, if a near miss will occur under the conditions at that precise moment and, if not, at what time in the future (if ever) it will occur. If the predicted "time to near miss" is less than the assumed critical reaction time, T , the pilot may be presumed to stand little chance of detecting the emerging aircraft and computing, or correcting his course to avoid the other aircraft. If, on the other hand, the "time to near miss" is greater than the critical reaction time, in this present analysis the pilot is assumed to have sufficient time to detect, evaluate, and avoid the other aircraft and the situation is no longer considered hazardous.

Experimental studies (1, 13, 20) have shown that subjects were able to judge collision conditions with relatively high accuracies (86%) while targets were still at long ranges. Their judgment accuracies improved as the target range decreased. Subjects also demonstrated the ability to successfully maneuver their own aircraft to avoid collision if given a reasonable time in which to react (approximately 20 seconds). (1) It can be tentatively assumed, therefore, that a target detected at a sufficient range to allow a decision and reaction on the part of the pilot poses little real threat even though it is initially on a near miss trajectory.

As a starting point for this analysis then, a hazardous near miss as defined here and used hereafter, must satisfy two conditions.

1. The future flight histories of the aircraft will both remain unchanged (no turns, no speed change, no change in rate of climb or descent) and will place the two aircraft within a predetermined miss distance, M , of each other; and
2. the time at which the aircraft come within distance, M , of each other must be less than some predetermined critical reaction time, T .

The value which one chooses for the critical miss distance, M , should be determined in such a way as to reflect the size of the aircraft involved, the uncertainty of the aircraft positions, the type of miss involved, (i.e. horizontal or vertical) and the safest proximity acceptable to pilots or passengers. In this present analysis the values of M were chosen dependent only on aircraft size. Because the geometrical equations developed below were normalized by aircraft velocity, v_1 , miss distance is expressed in terms of seconds (m) rather than feet (M). Thus, for an aircraft flying at 80 mph (117 ft/sec.) an m of 2 seconds is equivalent to an M of 234-feet miss distance. (As will be seen and discussed later in this report, the largest miss distance is set at 528 feet. While this might not seem "too close" in vertical distance, a pass that close directly across the bow might be regarded as a narrow squeak by many pilots, especially if the crossing aircraft were a 747 or a C5A whose wingspan consumed a large portion of that 528 feet.)

The value of T , as chosen for analytic purposes, should likewise reflect the total time required for the pilot to detect, evaluate, and react to an emerging aircraft; the responsiveness of the aircraft he is flying; and the emerging aircraft positional effects on detection; and other such features. This initial analysis, however, assumes merely that a constant reaction time of 20 seconds is needed by the pilot to detect and react to an emerging aircraft regardless of its location in the pilot's visual field, or other variables. It is readily acknowledged that this somewhat arbitrary selection is a gross oversimplification. It is well recognized the air-to-air target detection is a function of a host of variables including target position, time between appearance of targets, alertness of pilot, etc. It is known that pilots differ in the speed of their decision-making and their control actions, and that the aircraft vary tremendously in their aerodynamic characteristics in response to control actions by the pilot. However, there has to be a commencement point somewhere so a spatially constant detection and reaction function is assumed. The value of $T = 20$ seconds has been shown in a limited experimental study⁽¹⁾ to be probably reasonable and, since this number seems "about right" to many authorities including pilots, it has been accepted for use herein. It must be clearly understood that while this figure may be reasonable to use for a first analysis, it most assuredly should not be given uncritical acceptance. *Substantial further experimentation is positively required to get better data and to explore the results of using different reaction time assumptions.*

SECTION IV. SELECTION CRITERIA

In the preceding section a mathematical statement of a hazardous near miss encounter was developed using the initial position and subsequent behavior of the reference aircraft and the emerging aircraft as variables in the equation.

Equation (9) determines the scope of emerging aircraft headings which satisfy the hazardous near miss conditions previously specified. Such hazardous headings are a function of the chosen values for m , k and T as well as the initial positions of the respective aircraft.

One simple way to relate equation (9) to the problem of specifying safe aircraft-to-cloud separation limits and visibility limitations would be to find the initial emerging aircraft range and positions at which no headings of the emerging aircraft could be found to satisfy equation (9) and the near miss conditions. Thus, to determine acceptable aircraft-to-cloud separation minimums, simply find the value of the separation distance, D , related to the variables in equation (9) by:

$$(10) \quad d = \frac{D}{v_1}$$

$$(11) \quad \sin \epsilon = \frac{d}{r}$$

which produces no root of equation (9) in the range $0 \leq t \leq T$ for all allowable values of ϵ , δ , ψ , and Γ .

This technique is not completely satisfactory, however, since there is no *a priori* idea of how sensitive the near miss situation is to the separation distance, d . Because of the sharp cut-off on allowable hazard conditions imposed by setting an upper limit on t , namely T , the degree to which hazardous conditions exist just inside the minimum zero hazard boundary is not known. If, on the other hand, the near miss geometry decreases the number of hazardous solutions to equation (9) in a gradually tapering manner as d is increased, the number of hazardous solutions just inside the zero hazard boundary may represent a set of unique geometrical conditions, conditions which have only a remote possibility of occurring. These two hypothetical extremes are illustrated in Figure 7 where the relative number of hazardous near misses, N , are sketched versus the separation distance, d .

The cause for concern that either of these possibilities may exist is generated in the first case from safety considerations and, in the latter case, from economic factors. The possibility of sharp cut-offs imposed by an upper limit, T , on the roots of equation (9) places an inordinate dependency on the exact value of T that is chosen. Too small a T and many near misses would occur. Little conclusive experimental evidence exists from which to determine the correct and safest value of T ; only rough estimates can be made at present. It would hardly seem wise to base such a critical

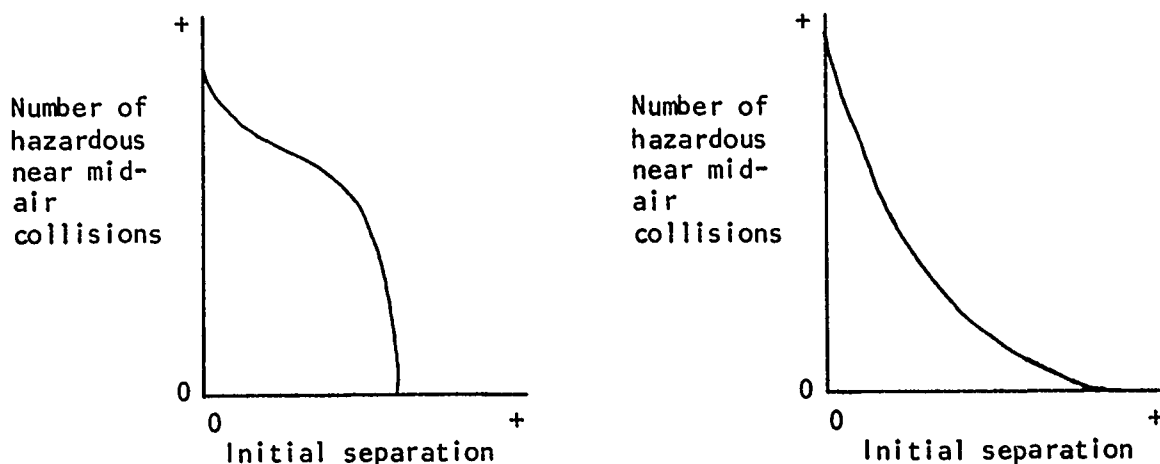


Figure 7. Number of Hazardous Near Mid-air Collisions
versus Initial Separation Distance of Emerging
Aircraft: Two Types of Hazard Boundaries

Federal Airways Regulation on a "best guess." The second alternative in Figure 7 represents perhaps an over concern for safety to the extent that it infringes on the economic feasibility of the separation regulation. Increasing the separation requirement would decrease the effective airspace available for VFR traffic as well as unnecessarily decrease the number of days of acceptable VFR flying conditions. The marginal increase in safety shown may hardly be worth the cost paid in lost flying time. The extent to which this decrease in flying time would occur cannot be predicted to any degree of accuracy with the existing weather data.* It is recognized, however that reduced VFR flying time would assuredly be one of the undesirable side-effects of overextending aircraft-to-cloud separation requirements and visibility requirements.

To guard against blindly falling into either of these extremes, something has to be known about the degree of hazard around the zero hazard boundary--something more than its mere location. Specifically, a "degree of hazard" has to be quantitized in some manner, computed at several separation distances, and plotted as a function of separation distance as in Figure 7. This is the approach that has been taken in this analysis.

The degree of hazard function developed for the present analysis is defined in the following manner. Assume a conditional probability function,

*The reason for this is that there does not appear to be any reliable data on the separation between scattered clouds, nor any data on the sizes of holes which exist in broken cloud situations. Lacking this information, one cannot estimate the frequency with which one could transit the cloud level while remaining VFR in accordance with a certain separation rule.

$P_{H/P}(\epsilon, \delta, r)$, can be generated which defines the probability of a hazardous near miss occurring given that an emerging aircraft appears at a particular initial position (ϵ, δ, r) with respect to the reference aircraft, where ϵ is the elevation angle to the initial position of the emerging aircraft with respect to the reference aircraft, δ is the relative bearing angle, and r is the slant range (in seconds) to the emerging aircraft at $t=0$. $P_{H/P}(\epsilon, \delta, r)$ is then a function of ϵ, δ , and r in the temporal volume surrounding the reference aircraft.

Integration of this function over a geometric surface gives the relative degree of hazard to be expected in having an emerging aircraft emanate from a point on the surface at $t=0$. Consider first a choice of surfaces which, by representing the horizontal surfaces of cloud boundaries, can be used to quantitize the vertical separation hazard.

If, in the same volume surrounding the reference aircraft a surface, $S(d)$, is defined to be a horizontal plane parallel to the flight path of the reference aircraft at a distance d from the reference aircraft, then a vertical degree of hazard, $H_V(d)$, is defined for a given separation standard, d , as:

$$(12) \quad H_V(d) = \int_{S(d)} P_{H/P}(\epsilon, \delta, r) \, d s$$

where the integration is taken over the surface $S(d)$. A completely "safe" vertical separation will produce a vertical degree of hazard equal to zero while larger positive values indicate an increasing hazard either through the extensive size of the non-zero hazardous area or through increased values of the probability function over a given area.

Lateral separation requirements can be analyzed in a similar manner by integrating over a vertical surface parallel to the flight path of the reference aircraft. As will be discussed in the next section, a considerable amount of computation is required to compute $P_{H/P}(\epsilon, \delta, r)$ at approximately 1000 points on a plane surface. This computation must be completed before the integration of the function $P_{H/P}(\epsilon, \delta, r)$ over the surface chosen can take place. In view of time and budget constraints, computation of $P_{H/P}(\epsilon, \delta, r)$ over both horizontal and vertical planes was not possible. Since the problem of vertical separation appears to be of foremost importance, $P_{H/P}(\epsilon, \delta, r)$ was computed for a vertical stack of horizontal planes only. This facilitates the analysis of the vertical separation standards, however, an alternate approach must be taken in reviewing the lateral separation and visibility standards.

Inspection of the computer results for the horizontal plane computations at various vertical separation values indicated, as could be expected, that the total hazard is greatest on the $d=0$ plane and decreases monotonically as d increases. If the lateral separation hazard is then computed only at the intersection of the vertical plane representing a vertical cloud boundary and the horizontal reference plane (i.e. along a line on the horizontal reference plane parallel to the x axis and at a distance from the x axis equal to the

lateral separation distance under test), then the value found will decrease monotonically as the separation distance increases and in a manner similar to the integration of the hazard probability over the entire vertical plane. In other words, the simplified integration along a line approximates the full integration over an entire vertical surface, at least in the relative sense, as the line or plane moves away from the x axis. The integration along this line is defined in this report, then, as the lateral degree of hazard, $H_L(y)$, where y is the lateral distance to the cloud boundary (in seconds, since it is normalized by v_1 , the reference aircraft velocity).

$$(13) \quad H_L(y) = \int_{\text{at } y} P(\epsilon, \delta, r) \, dx$$

Using the same reasoning, the horizontal visibility minimums can be found by integrating $P_{H/p}(\epsilon, \delta, r)$ over a sphere of radius, r ; or, as was done in the present analysis, by integrating $P_{H/p}(\epsilon, \delta, r)$ around the perimeter of a co-planar horizontal circle surrounding the referenced aircraft. This function, the radial degree of hazard, $H_H(r)$, is normalized by the value of the circumference of the circle.

$$(14) \quad H_H(r) = \frac{1}{2\pi r} \int_0^{2\pi} P(\epsilon, \delta, r) \, d\delta$$

These three hazard functions $H_V(d)$, $H_L(y)$, and $H_H(r)$ can be used to assign numerical values to what has normally been treated as a non-dimensionable quality "hazardousness." A caution must be given that no specific meaning can be attached to the numerical value per se. However, the important point here is that a way has been found for the application of numerical values to the relative degree of hazard between situations. Thus, one set of standards may be shown to be ten times more hazardous than another. These numbers should be interpreted most carefully, however, since the exact numerical values obtained from this process *do not give an absolute value for the probability of a near miss occurring*. Even ratio comparisons such as "ten times greater than," are in essence, still value judgments since hazardousness is generally intuitive, lies somewhat in the risk-taking propensities of the person experiencing the risk and is not directly quantifiable. If the concept of hazardousness is accepted as being defined by a numerical function and the associated concept of numerical ratios having meaning in comparing degrees of hazardousness, then the following analysis and interpretation of the results proceeds forthrightly. The utility of these functions will become more apparent later as Figures 38 through 46 are inspected.

Conditional collision probabilities, such as $P_{H/p}(\epsilon, \delta, r)$, have been previously defined⁽¹²⁾ as the ratio of the range of heading or bearing angles at a particular point that would lead to a near miss to the entire range of possible heading or bearing angles allowable. The exact definition is dependent on the geometrical variables used to describe the near miss situation. From the construction used above, the relative heading ψ , and flight path angles Γ , of the emerging aircraft are the independent variables to be incorporated in the definition of $P_{H/p}(\epsilon, \delta, r)$. Thus $P_{H/p}(\epsilon, \delta, r)$ is the ratio

of the set of emerging aircraft relative heading and flight path angles, ψ and Γ respectively, which satisfy the near miss conditions to the total set of ψ 's and Γ 's permissible at that point in space (ϵ, δ, r).

$$(15) \quad P_{H/P}(\epsilon, \delta, r) = \frac{\{(\psi, \Gamma)_{\text{near miss}}\}_{\epsilon, \delta, r}}{\{(\psi, \Gamma)_{\text{permissible}}\}_{\epsilon, \delta, r}}$$

The set, $\{(\psi, \Gamma)_{\text{near miss}}\}$, are those values of ψ and Γ which, for the given values of ϵ, δ , and r , produce roots of equation (9) such that $0 \leq t \leq T$. The set, $\{(\psi, \Gamma)_{\text{permissible}}\}$ defines the possible directions in which the obscured aircraft may head. For this analysis ψ is allowed to vary from 0° to 360° while Γ is restricted to $\pm 10^\circ$. Implicit in the definition of $P_{H/P}$ as given in equation (15) is the assumption that all of the ψ, Γ combinations in $\{(\psi, \Gamma)_{\text{permissible}}\}$ are equally likely. Obviously, in particular situations such as in the convergence of airways in the vicinity of vortac station or letdowns to the outer marker, etc., this assumption is not true and would have to be modified. However, this is the general case and in the face of no necessity to consider special cases at this time this assumption is a valid one which will give a universally acceptable outcome for the generalized VFR flight case.

SECTION V. COMPUTER ANALYSIS

The direct computation of the integral in equation (12) requires an explicit expression of $P_{H/P}(\epsilon, \delta, r)$ as a function of ϵ, δ , and r over the entire cloud surface $S(d)$. This, in turn, requires an explicit solution for the set $\{(\psi, \Gamma)_{\text{near miss}}\} \epsilon, \delta, r$. The complexity of equation (9) precludes finding any manageable forms of such expressions; therefore, an alternate approach was taken.

To determine the vertical degree of hazard, $H_V(d)$, the integral in question can be approximated by summing values of $P_{H/P}(\epsilon, \delta, r)$ at discrete points on the cloud surface $S(d)$ and multiplying the sum by an area proportionate to the spacing of the discrete points as in equation (16).

$$(16) \quad \int_{S(d)} P_{H/P}(\epsilon, \delta, r) ds \approx \Delta^2 \sum_N P_{H/P}(\epsilon, \delta, r)$$

where N is the number of discrete points and Δ^2 is the area associated with each point.

Using the strength of a high speed digital computer, the set $\{(\psi, \Gamma)_{\text{near miss}}\} \epsilon, \delta, r$ can be determined by testing values of ψ and Γ with a given ϵ, δ , and r in equation (9) to find those values which satisfy the two hazardous near miss conditions. Doing this at each discrete point on $S(d)$ and summing the values of $P_{H/P}(\epsilon, \delta, r)$, the degree of hazard can be computed for a given set of parameters: k, m , and T ; and at a given separation distance, d .

Since the integration is to be performed over a plane above the reference aircraft (to simulate the instance where an intruding aircraft descends out of clouds) a Cartesian coordinate system would seem appropriate for locating points on the cloud surface. Remembering that all dimensions in this analysis are reduced by v_1 and therefore appear in terms of seconds, the following relations illustrated in Figure 8 exist between points on the cloud surface (x, y) and variables in equation (9):

$$(17) \quad x = \frac{x}{v_1}$$

$$(18) \quad y = \frac{y}{v_1}$$

$$(19) \quad r^2 = x^2 + y^2 + d^2$$

$$(20) \quad \sin \delta = \frac{y}{\sqrt{x^2 + y^2}}$$

$$(21) \quad \cos \delta = \frac{x}{\sqrt{x^2 + y^2}}$$

$$(22) \quad \sin \epsilon = \frac{d}{\sqrt{x^2 + y^2 + d^2}}$$

$$(23) \quad \cos \epsilon = \frac{\sqrt{x^2 + y^2}}{\sqrt{x^2 + y^2 + d^2}}$$

Equation (9) reduces to:

$$(24) \quad (1 + K^2 - 2 K \cos \Gamma \cos \psi) t^2 + 2 \{ K (x \cos \psi + y \sin \psi) \cos \Gamma - x + K d \sin \Gamma t \} + x^2 + y^2 + d^2 - m^2 = 0$$

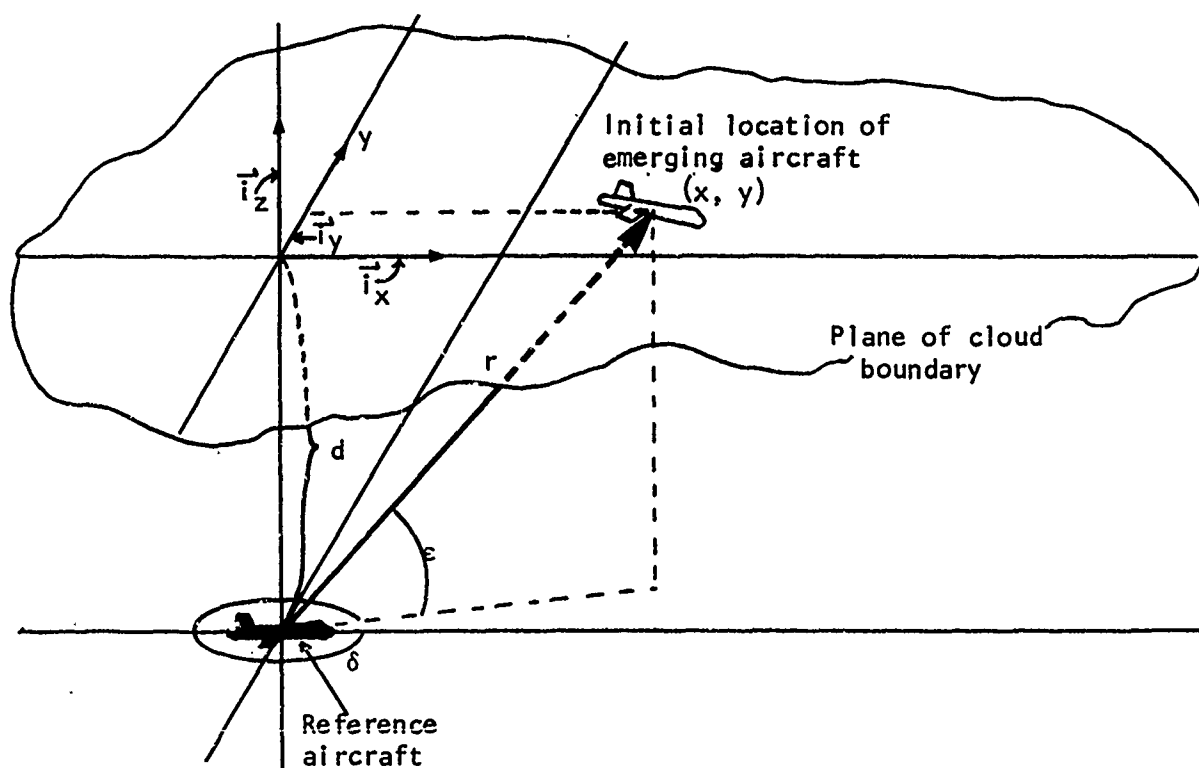


Figure 8. Relation of Points on Cloud Boundary Surface to Initial Position Coordinates

In performing the computer analysis, equation (24) was not solved for every ψ , Γ pair; rather a root algorithm was used to test for the hazardous near miss conditions. A complete program listing can be found in Appendix A.

In the computer analysis, it was assumed that the emerging aircraft could appear at any of a very large number of predetermined places at various distances around the reference aircraft. The actual locations and distances of assumed emergence were scaled in terms of time. For example, 20 seconds off to the right and 16 seconds ahead and 4 seconds above could identify a specific starting point. The heading of the emerging aircraft at the instant of emergence was systematically varied to all headings between 0° and 355° by 5° increments. Thus, at some headings the two aircraft would be on converging headings, on others diverging headings, and on still others would be headed in opposite directions on parallel courses. Obviously, only a certain number of the headings would be capable of generating tracks intersecting the near miss sphere of the reference aircraft. Because of vertical symmetry in this analysis, only threats on the reference plane or above were considered. Therefore, the angle of descent (Γ) was incremented between 0° and -10° by 1° increments. The point of origin of the emerging aircraft on the hypothetical cloud was systematically incremented starting at the hypothetical x , y , z point: $x = -x_{\max}$, $y = 0$, $z = d$, where $-x_{\max}$ is the extreme point in the $-x$ direction from which a hazard could arise (this will be discussed in detail further on in this report). The size of the increment varied for a given set of parameters depending on the scale being experimented with in the analysis. The general intent of changing the scale was to cause the analysis to utilize approximately the same number of data points for each analysis in spite of changes in geographic space covered. On the average, approximately 1100 origination points were computed on the hypothetical cloud surface for each run.

Several simulations were made for each type of confrontation in order to determine the influence of adopting a given altitude separation rule (separation on z -axis). At first, the two aircraft were placed at the same altitude and a computer output for $d=0$ was obtained. The emerging aircraft plane (i.e., test cloud boundary) was then raised to a different altitude, d , and another run made, etc. In this way the horizontal test planes were systematically started farther and farther above the reference plane until the computer runs showed a trivial number of near-misses or that the next altitude separation would probably produce no near misses at all. At that point the assumption was made that the two aircraft had been given sufficient separation that their likelihood of being able to hit each other within time T had become near zero. Since this was a "cut and fit" simulation task at this stage, several runs were made to explore the influence of different separations (see Table 3). The results of a selection of these runs are plotted in this report as Figures 11 through 37 and as Figures 38 through 46. *Thorough understanding of these figures is absolutely fundamental to understanding of the conclusions of this report.* The following pages explain how these figures were obtained and what they mean.

In each instance, in Figures 11 through 37, the emerging aircraft originates at a point on the plane depicted in the figure at the instant the reference aircraft is at its origin. The figures are essentially snapshots of possible initial positions of the emerging aircraft on a cloud boundary at $t=0$. The unique feature of these snapshots is that they predict the future

outcome of the encounters in terms of their hazard probability. Using the mathematical tests expressed in equation (9) a "score" is achieved by determining if the projected flight path does or does not intersect the near miss sphere of the moving reference aircraft within time T , during the confrontation. Record was made of the number of near misses vs. the total number of flights and this ratio used to generate a probability of a hit (e.g., 0.026 indicates that about 3% of the possible flight paths originating at this point, under these conditions, would produce a near miss).

The computer running times required in this analysis were fairly long and since sufficient funding was not made available only an extremely narrow selection of run parameters, to cover the widest range of situations, was made. The largest number of aviators who would be affected by changes in VFR regulations would probably be General Aviators, so that the aircraft encounters analyzed here have been caused to center on confrontations between 1) typical light, low speed aircraft; 2) General Aviation aircraft operating a normal cruise (or large aircraft maneuvering in the terminal area); and 3) high subsonic speed aircraft such as cruising transport jets. These three "types" of aircraft were matched against each other resulting in nine types of encounters. Table I summarizes the run parameters as the emerging aircraft across the top are matched against the reference aircraft along the left side of the table.

The first aircraft type (Class I) represents a low-speed single-engine light aircraft, archetype of aircraft used by student pilots and "pleasure only" aviators. This also constitutes the edge of the speed domain for either V_{mc} or approach speed for many higher performance General Aviation single engine and light twin aircraft. This aircraft class was assigned a velocity of 80 mph (117 ft/sec) and a near miss sphere of a 234-foot ($m = 2.0$ seconds) radius. This is the same as surrounding the reference aircraft with a 234-foot diameter bubble. Then, if the trajectory of the emerging aircraft touches the "bubble" of the reference aircraft at any time within time T , a near miss is declared. In actual operations, a miss of 234 feet, especially if from a crossing course or opposite course, seen only for the last couple of seconds before passage, would be regarded by most as a pretty close shave, so the criterion is a rather scary one.

The second aircraft type (Class II) is assigned a 170-mph (250 ft/sec.) velocity and a 500-foot ($m = 2$ seconds) near miss sphere radius. This class of aircraft more or less represents the high performance single-engine or light twin engine aircraft at its normal cruising speed, and the jet transport or military aircraft slowed down and maneuvering in the terminal area. Selection of these two types was made to maximize the analytical coverage of the traffic confronting the general aviator as well as much of the "low and slow" encounters of the big high-performance transport and military aircraft.

A third aircraft class (Class III) covers encounters between high speed commercial jet and military jet aircraft. Because they generally tend to operate at different altitude strata, encounters between jets at full speed (Class III aircraft) and General Aviation traffic (Classes I and II) occur relatively infrequently compared with other mixes. However, according to participants, when such encounters do occur they sometimes implant memorable experiences in the minds of all the aviators concerned. The jet aircraft in

TABLE 1. CHARACTERISTICS OF AIRCRAFT ENCOUNTERS

Reference Aircraft	Emerging Aircraft					
	Class I		Class II		Class III	
	m	k	m	k	m	k
Class I	2.0	1.0	2.0	0.5	0.6	0.1
Class II	4.5	2.0	2.0	1.0	0.6	0.3
Class III	4.5	7.5	2.0	3.5	0.6	1.0

m = radius of miss distance sphere surrounding reference aircraft, expressed in seconds, at the velocity of the emerging aircraft

k = approximate relative speed ratio of the two aircraft in confrontation, e.g.

$$\frac{\text{Class I}}{\text{Class II}} = \frac{117}{250} = \text{approx. } 0.5 \text{ rounded}$$

Class I Aircraft Speed = $v = 80 \text{ mph} = 117 \text{ ft/sec}$
Miss distance where $m = 2 = M = 234 \text{ feet}$
where $m = 4.5 = M = 526 \text{ feet}$

Class II Aircraft Speed = $v = 170 \text{ mph} = 250 \text{ ft/sec}$
Miss distance where $m = 2 = M = 500 \text{ feet}$

Class III Aircraft Speed = $v = 600 \text{ mph} = 880 \text{ ft/sec}$
Miss distance where $m = 0.6 = M = 528 \text{ feet}$

Note: The intent of selecting the values shown for m was to generate miss distances of approximately 500 feet (except for the Class I vs. Class I confrontations where a miss distance of almost half again as close as the others was sought to see what effects this would have on the outcome of the data.

this model (Class III) is characterized by a 600-mph (880 ft/sec) velocity and a 528-foot* (0.6 seconds) miss radius.

In Table 1, in matching one aircraft type against another k is found from the ratio of airspeeds; m is chosen from the larger of the M values for the aircraft involved, expressed in terms of the reference aircraft's velocity.

The longitudinal symmetry of the near miss geometry allows a complete analysis to be made by analyzing only half the cloud surface, $S(d)$. That is, the integral in equation (12) can be found by doubling the value of the integration of $P_{H/P}(x, y, d)$ from the boundary $-x_{\max}$ to $+x_{\max}$ and 0 to $+y_{\max}$. This approach greatly reduces the computer run time, particularly when values of $-x$, $+x$, and y can be chosen just past the points where $P_{H/P}(x, y, d)$ goes to zero. Similarly it is not necessary to run the problem for both cases where the emerging aircraft drops out of an overcast down to the altitude of the reference aircraft, or climbs up beneath the reference aircraft by coming up out of an undercast. The geometry is the same in both instances assuming that aircraft actually make climbs and descents at the same rate. Any findings which lead to a flight standard for vertical separation from clouds would apply to VFR operations either above or below cloud. Although there does not appear to be any readily available evidence on this point, it seems that in actual practice many aviators tend to let down at slower rates than they climb out. Hence, the effect of any rule requiring the same separation above and below cloud would probably make things safer for let-downs than for climbouts. It is an interesting issue, and one on which data should probably be collected.

Estimates of $-x$, $+x$, and $+y$ at which $P_{H/P}(x, y, d)$ goes to zero, as well as the maximum separation distance d_{\max} , can be made by inspecting worst case conditions. The most spatially extensive near-miss conditions in an x - y plane must of necessity exist when both aircraft are co-planar, i.e., when $d = 0$. In this case, it can be seen from the construction in Figure 9 that the following relations hold:

$$(22) \quad x_{\max} = 20 (k + 1) + m$$

$$(23) \quad -x_{\max} = 20 (k - 1) + m$$

$$(24) \quad y_{\max} = 20 k + m$$

$$(25) \quad d_{\max} = m + 20 k \sin 10^\circ$$

*Normal practice was to make $m = 2$ in Class I and Class II aircraft. However, if this is done in Class III aircraft the miss distance would have to be defined as 1760 feet, which is obviously too large. Hence the change to 0.6 seconds for m which yields a value of 528 feet ($0.6 \times 880 = 528$) which may be defined as a "reasonable distance" by which to miss.

As mentioned in the previous section, it is desirable to know the behavior of the degree of hazard function in the vicinity of the zero hazard boundary. To accomplish this, the function $H(d)$ was computed at $d = 0$,

$d = \frac{d_{\max}}{2}$, and a third value just less than d_{\max} . The full listing of run parameters used in the analysis is given in Table 2.

The values of k and m computed for the selected encounters were used to compute x_{\max} , $-x_{\max}$, y_{\max} and d_{\max} . These values are also listed in Table 2.

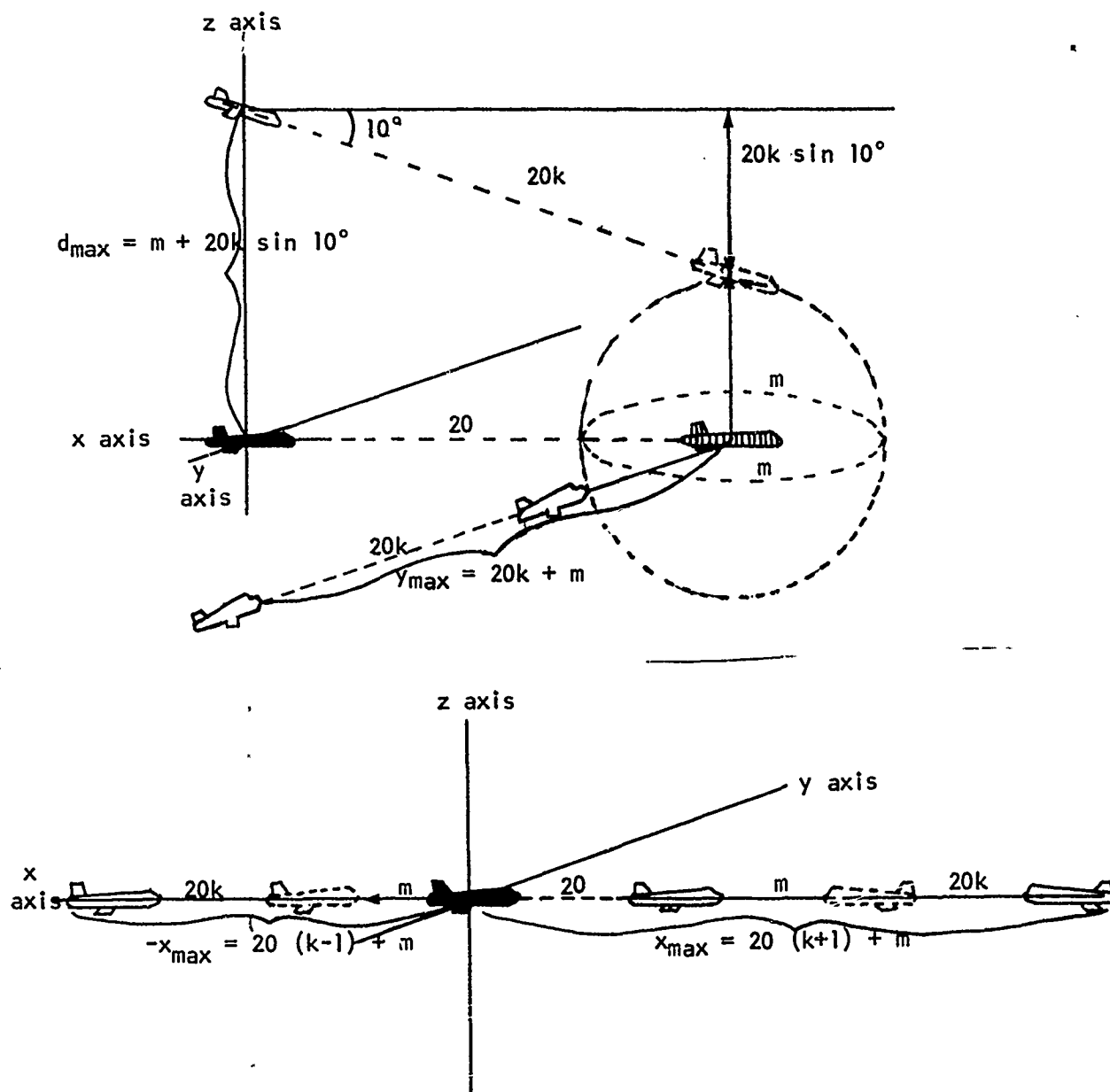


Figure 9. Maximum Distances for Possible Hazardous Near Misses

TABLE 2. COMPUTER RUN PARAMETERS

Class		Fig.	m	k	d	-x	x	y	x-y Increment Size*
I	Vs. I	{11	2.0	1.0	0.0	10	50	30	1.0
		{12	2.0	1.0	3.0	10	50	30	1.0
		{13	2.0	1.0	5.0	10	50	30	1.0
	Vs. II	{14	4.5	2.0	0.0	40	70	50	2.0
		{15	4.5	2.0	5.0	40	70	50	2.0
		{16	4.5	2.0	10.0	40	70	50	2.0
	Vs. III	{17	4.5	7.5	0.0	150	200	180	7.0
		{18	4.5	7.5	15.0	150	200	180	7.0
		{19	4.5	7.5	30.0	150	200	180	7.0
II	Vs. I	{20	2.0	0.5	0.0	+10	50	50	2.0
		{21	2.0	0.5	1.5	10	50	50	2.0
		{22	2.0	0.5	3.0	10	50	50	2.0
	Vs. II	{23	2.0	1.0	0.0	10	50	30	1.0
		{24	2.0	1.0	3.0	10	50	30	1.0
		{25	2.0	1.0	5.0	10	50	30	1.0
	Vs. III	{26	2.0	3.5	0.0	70	100	100	4.0
		{27	2.0	3.5	7.0	70	100	100	4.0
		{28	2.0	3.5	14.0	70	100	100	4.0
III	Vs. I	{29	0.6	0.1	0.0	2	30	5	0.4
		{30	0.6	0.1	0.5	2	30	5	0.4
		{31	0.6	0.1	0.8	2	30	5	0.4
	Vs. II	{32	0.6	0.3	0.0	+2	40	10	0.5
		{33	0.6	0.3	0.8	2	40	10	0.5
		{34	0.6	0.3	1.5	2	40	10	0.5
	Vs. III	{35	0.6	1.0	0.0	2	50	30	1.0
		{36	0.6	1.0	2.0	2	50	30	1.0
		{37	0.6	1.0	3.75	2	50	30	1.0

*x-y increment size deliberately manipulated so as to produce roughly the same number of data points for each computer run. No other special implications should be ascribed to the choice of increment size.

SECTION VI. DISCUSSION OF RESULTS

Two major outputs were obtained in printed form from the computer runs: x-y plots which could be converted to the conditional probability, $P_{H/P}$ (x, y, d), and the summations of the probability function over the horizontal surfaces examined.

Part A - Conditional Probabilities of Near Misses

An example of a typical x-y plot is shown in Figure 10. The matrix of numbers represent the number of ψ , Γ pairs of the emerging aircraft which satisfy the hazardous near miss conditions. (For the angular increment size used in this particular analysis the maximum number of potentially hazardous pairs happens to be 1533. To convert these numbers to conditional probability values simply multiply by 0.00065. For example, a value of 75 is equivalent to $P_{H/P} = 0.04875 = 0.05$.)*

A complete set of all 27 conditional probability plots listed in Table 2 is presented in the following section of this report. They are grouped in threes, arranged by type of encounter, so as to reveal the pattern that develops as each class of aircraft encounters each other class of aircraft under different hypothetical separation standards.

Let us go through these figures at this time, reserving general comments until after these figures have been shown. The plots themselves are extremely significant to this study and to other related fields of study, as will be discussed in subsequent sections of this report.

The plots of a given class of reference aircraft versus a given class of emerging aircraft are scaled identically to illustrate the magnitude of the differences involved in the various encounters. *However, there are differences between the scales on various different aircraft types and this fact needs to be carefully noted.*

Figures 11, 12, and 13 show the outcomes when a Class I aircraft comes into an encounter with another Class I aircraft. Note that the speeds of both aircraft are identical ($k = 1$), and that the miss distance criterion ($m = 2$) [or 234 feet of travel of the reference aircraft along its trajectory] is the same in all three figures. All three plots are on the same scale. What is changed between Figures 11, 12, and 13 is the vertical separation between

*This is the kind of conversion which has been done to the raw data to generate Figures 11 through 37). Note that the first line of printout specifies the values of d, m, k, the negative and positive limits of x, the size of the x increment, the maximum value of y, and the y increment size. Both x and y are incremented by the same amount, Δ . To find the x-y coordinates of a given matrix entry, starting at the top of the printout count down the number of computer lines to the entry, add one, and multiply by the increment size, Δ ; add this to the negative x limit to find the value of the x coordinate; the y coordinate is found likewise using the columns instead of the lines and starting at the lefthand side of the printout.

**Figure 10. Example of P_H/P Plot from Computer Run
(Class 1 Aircraft vs. Class 1 Aircraft)**

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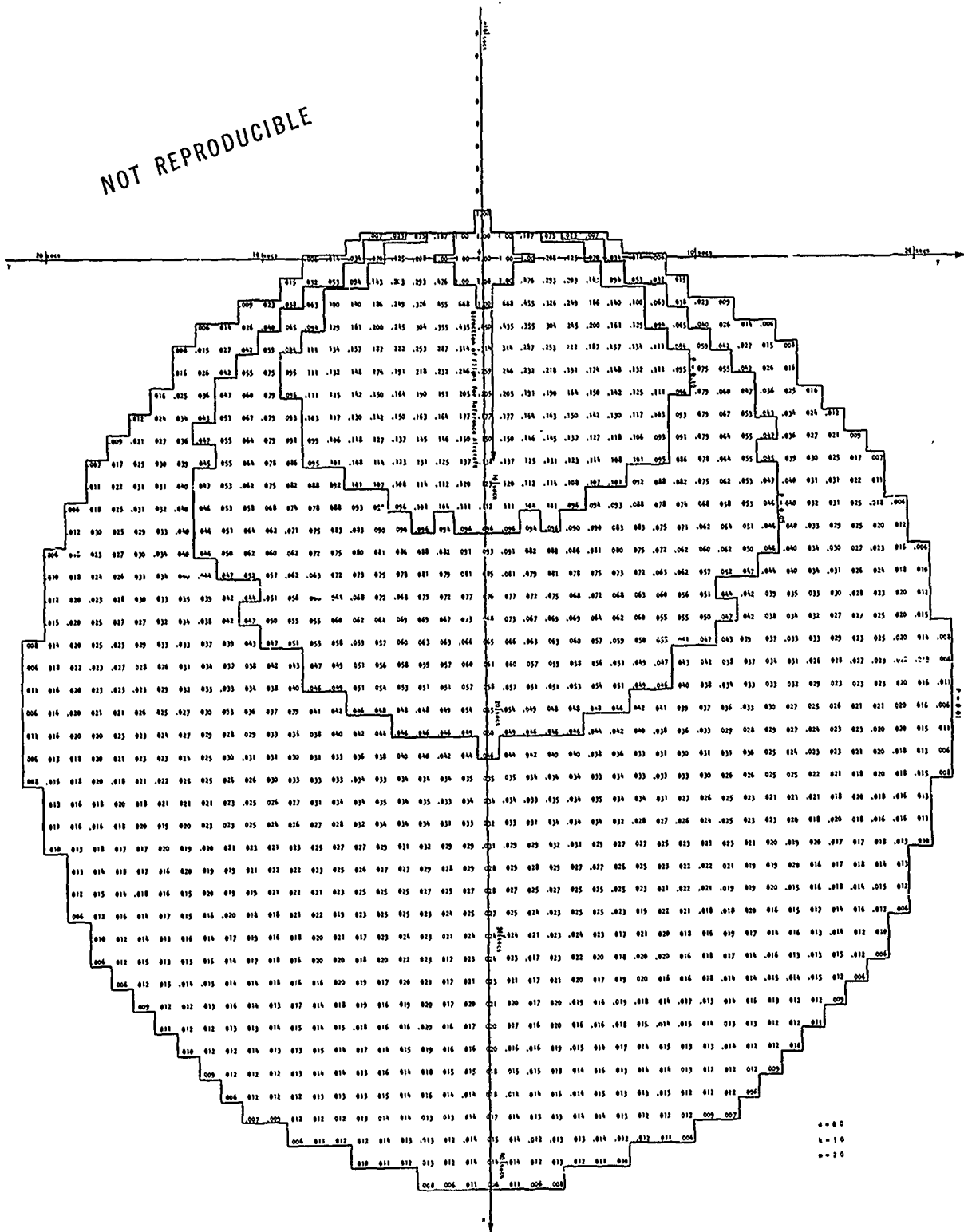


Figure 11. Probability Integral Over x-y Plane
Class 1 vs. Class 1

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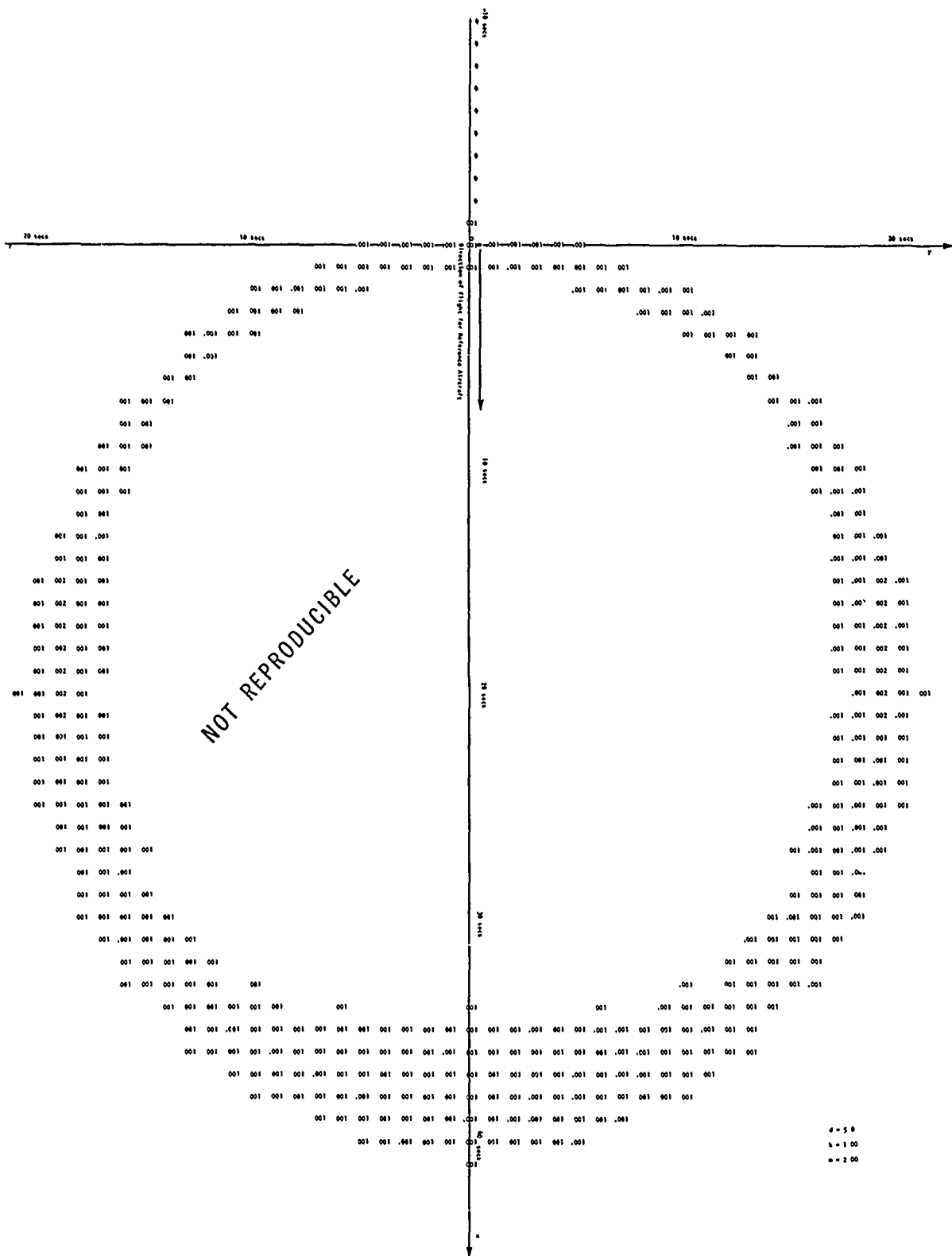


Figure 13. Probability Integral Over x-y Plane
Class 1 vs. Class 1

aircraft at the instant the emerging aircraft erupts from cloud above (or below) the horizontal plane of the reference aircraft. Figure 11 makes the assumption that both aircraft are on precisely the same plane at the moment the problem starts, that the reference aircraft starts along the x-axis at $t=0$ and, further, that the emerging aircraft can be assumed to be on any heading and altitude change rate allowed in this simulation. Both aircraft are assumed to fly straight, unaccelerated courses without any evasive maneuver. The data in Figure 11 simply says that if, at the position indicated by the x-y coordinates, an aircraft were to emerge at that location and fly in all the directions it might choose ($0-355^\circ$ by 5° increments) at all glide slope angles from -10° to ϕ (by 1° 's), the emerging aircraft would achieve a near miss with the reference aircraft that per cent of the time shown in the figure.

From inspection of Figure 11 it is noted that if the emerging aircraft is within 2 seconds of the reference aircraft at starting time in the problem it must, by definition, be making a near miss no matter what its heading or altitude change may be. However, if the emerging aircraft is simply started from a position directly 3 seconds to the right of the reference aircraft, the probability of making a near miss plummets to .208.

To help grasp the data in the first figure the boundary zones have been traced out where the probabilities of making a near miss are 1.00, 0.10, 0.05, and 0.01. In this particular figure, any number lying outside the outermost boundary was computed to have a probability less than 0.005. In order to avoid cluttering up the figures we have not drawn the boundary zones on other than Figure 11. In addition to clutter, the construction of probability profiles seems to carry something of an implication that a certain boundary, say the 0.05 or the 0.01, is a limit which divides "safety" from "disaster." At this time it would really be preferable to simply show the data and reserve the setting of limits (or, more correctly, the promulgation of hypothetical separation standards) to a later stage in the report when the full impact of the data plus some further mathematical analyses have been seen. The reader is, of course, free to try his own analysis and is encouraged to do so.

As will be found in subsequent sections of this report, ways have been found to compute hypothetical horizontal cloud separation standards and horizontal flight visibility standards from the $d=0$ charts obtained in the simulation. For the moment only vertical separation data is being considered.

Examination of Figures 12 and 13 will produce an understanding of the influence of vertical separation. In brief, they show that as vertical separation, d , is increased, the probabilities of making a near miss are dramatically reduced. For example, the highest probability that can be found in Figure 12 (3-second vertical separation) is a mere 0.025 while on Figure 13 (5-second separation) is reduced an order of magnitude to 0.002. Obviously, in this particular kind of confrontation between these classes of aircraft even a little vertical separation buys an awful lot of protection!

Furthermore, as the trend in Figures 12 and 13 shows in a most intriguing way, there are literally enormous areas from which one aircraft cannot hit the other (assuming the reaction time given in this simulation). There will be more discussion of the figures as a group after all the data has been shown.

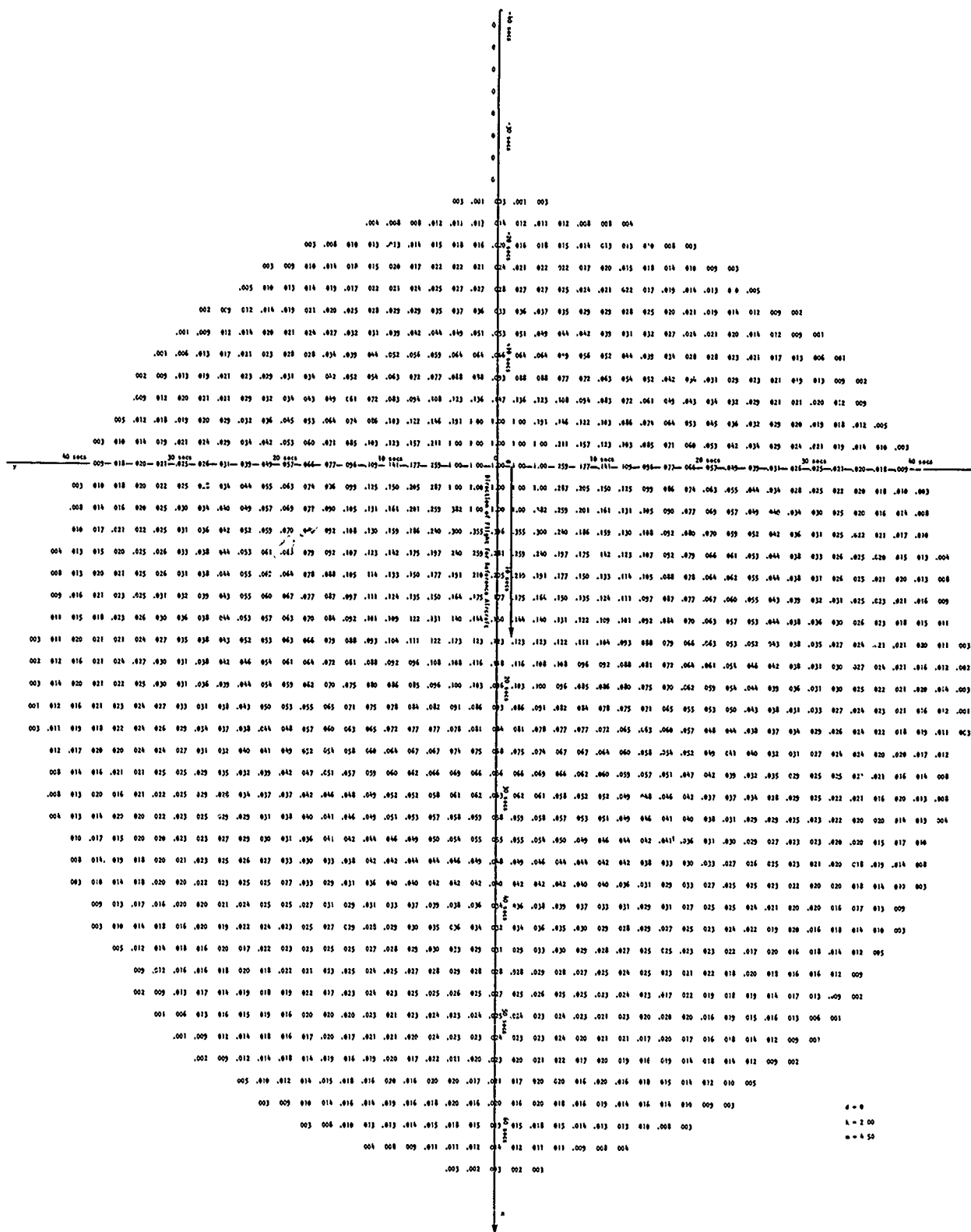
Figures 14, 15, and 16 show the results of a hypothetical series of confrontations with a Class I reference aircraft being confronted by a Class II emerging aircraft ($k = 2.0$ means the emerging aircraft is twice as fast as the reference aircraft). As an experiment, partly in order to explore its influence, and partly to make a larger near miss sphere to give "more protection" against a faster aircraft, the miss criteria was changed to 4.5. [In Class I vs. Class I confrontations (Figures 11, 12, and 13) 2.0 was used which gives a 234-foot radius near miss sphere; in the Class I vs. Class II confrontation (Figures 14, 15 and 16) 4.5 was used which gives almost a 500-foot radius sphere.]

The reader should also note that Figures 14, 15, and 16 are plotted on a different scale from that on Figures 11, 12, and 13. This was done to roughly equalize the number of data points and to keep down demand on the computer. It is plotted by 2-second time increments but is displayed on the same sized plot in both series. The way this is plotted has undesirable effects since it fails to reveal the change of scale of geographic area encompassed by the various confrontations because it prints them on the same scale. A way could not be devised to beat this problem and still have the data remain readable in the report. Hence, the reader must remain alert to these scale changes in the figures and mentally adjust the geographic scale of the confrontation. It is quite important to make this adjustment lest severe misinterpretations of the data result.

Attention is drawn to the influence of changing the k scale, the m scale, the fact that a much larger d factor is required in order to bring the probabilities down to acceptable limits (as in Figure 16), and that the confrontations remain high probability out to a somewhat larger distance than in I vs. I confrontations (a 20-second radius in Figure 11 versus about a 40-second radius in Figure 14). Note also that in this series instances may be observed for the first time where the emerging aircraft can "get" the reference aircraft from behind. This is because of the speed differential of the emerging aircraft, of course; a slower aircraft patently cannot run down a faster aircraft from behind. It shows the case where the slow airplane is sometimes said to "back into" the following aircraft!

Figures 17, 18, and 19 depict a Class I reference aircraft versus a Class III emerging aircraft. Note again the change of scale. Note also that for reasons of economy the data has been computed only in very coarse intervals (7-second increments). This produces a coarse grained analysis so that the magnitude of probability boundaries is less precisely defined than has been the case in the previous analyses. At this time there is no decision as to why the data turns out somewhat square-shaped as opposed to roundish or pear-shaped, as others in the series have been. This lack of knowledge is one of the many reasons why it is believed that the present exploratory study is well worth further pursuit.

Figure 19 shows the outcome of choosing a value for d exactly equal to or greater than the value of d_{max} . Using the model parameters listed, no near miss encounters were generated as indicated by the blank field in the figure. Presumably, if the model were run at a slightly lower value of d , say $d=28$, a pattern of encounter hazards would appear. The use of discrete heading and glide slope increments for the emerging aircraft may not guarantee the



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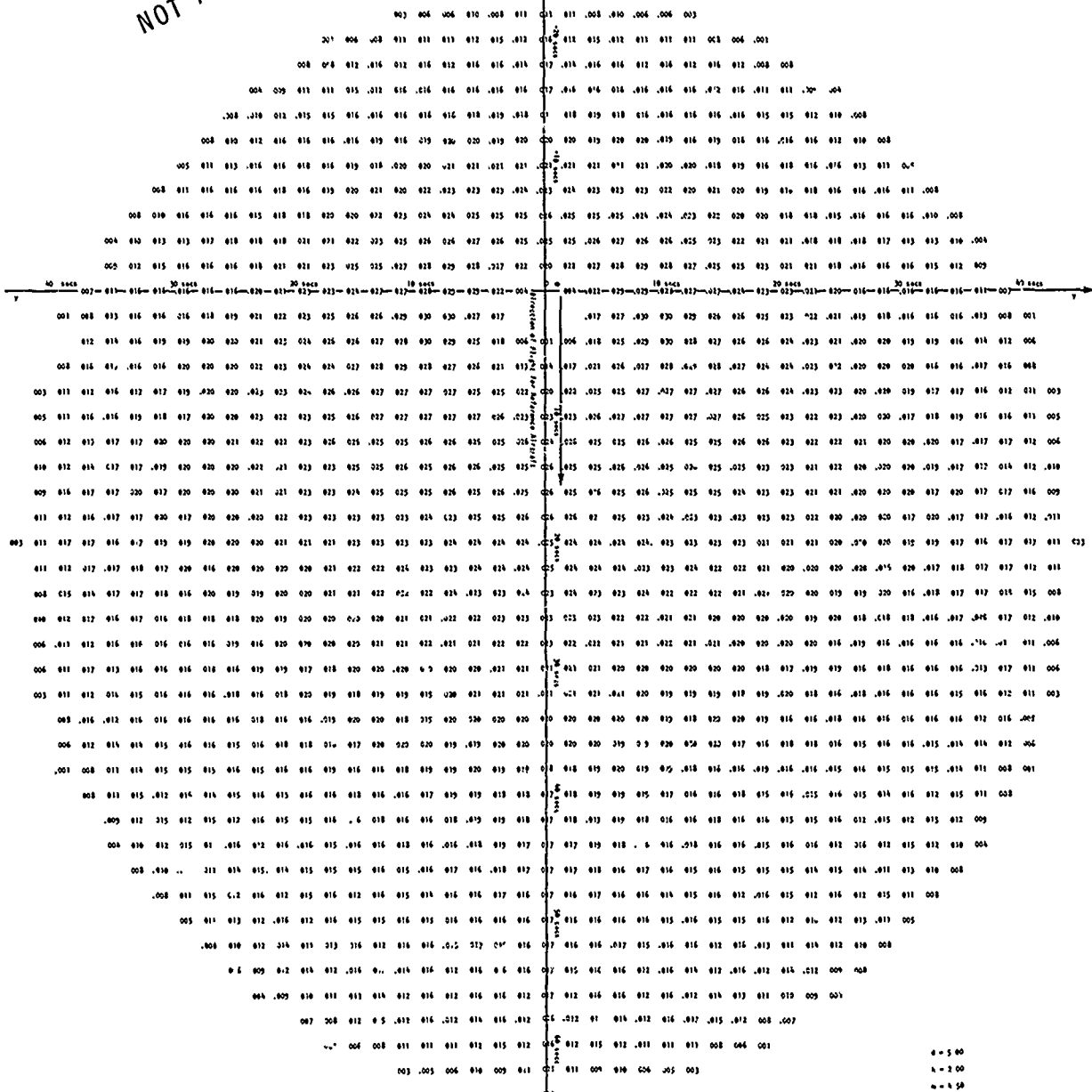


Figure 15. Probability Integral Over x-y Plane
Class 1 vs. Class 11

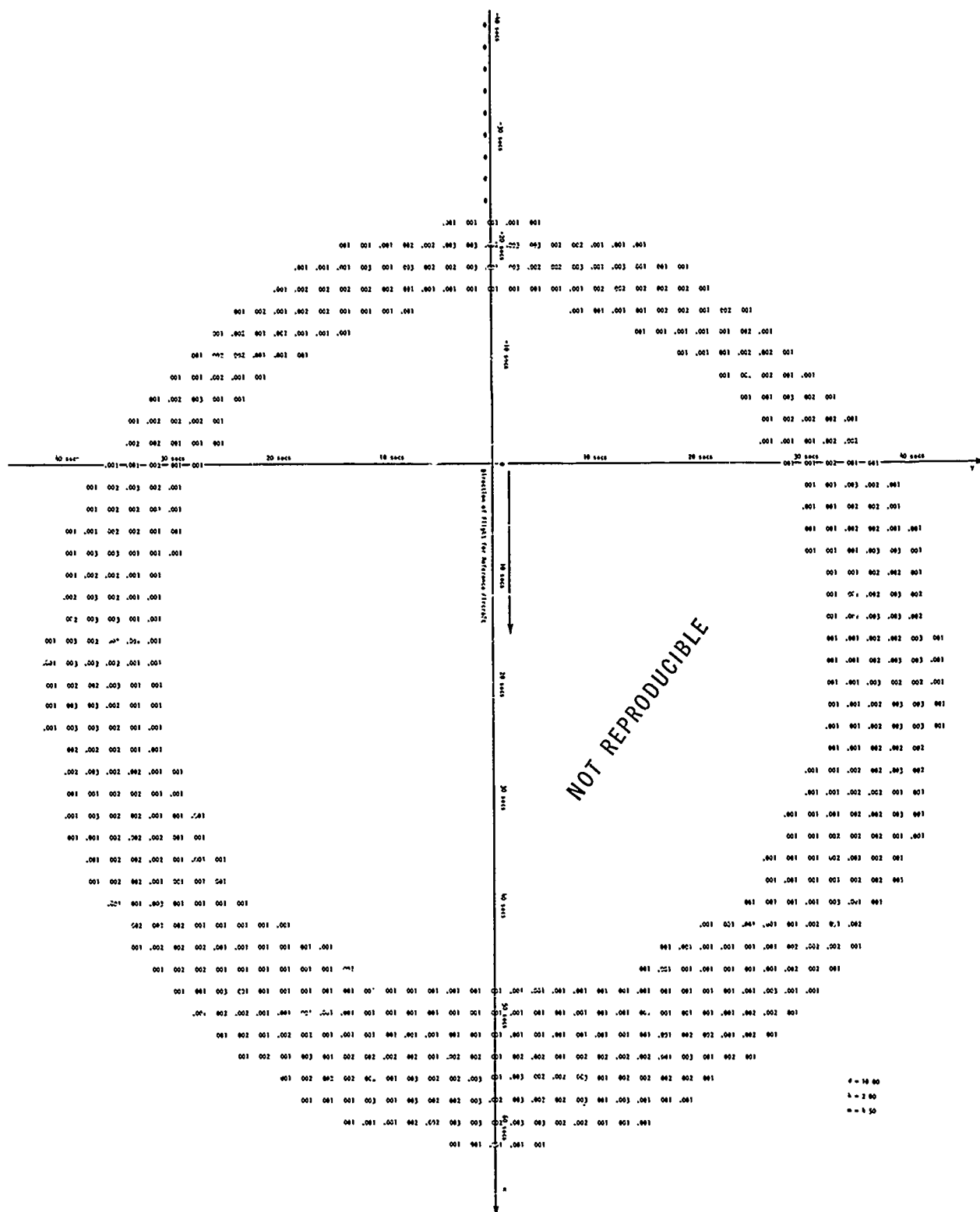


Figure 16. Probability Integral Over x-y Plane
Class 1 vs. Class 11.

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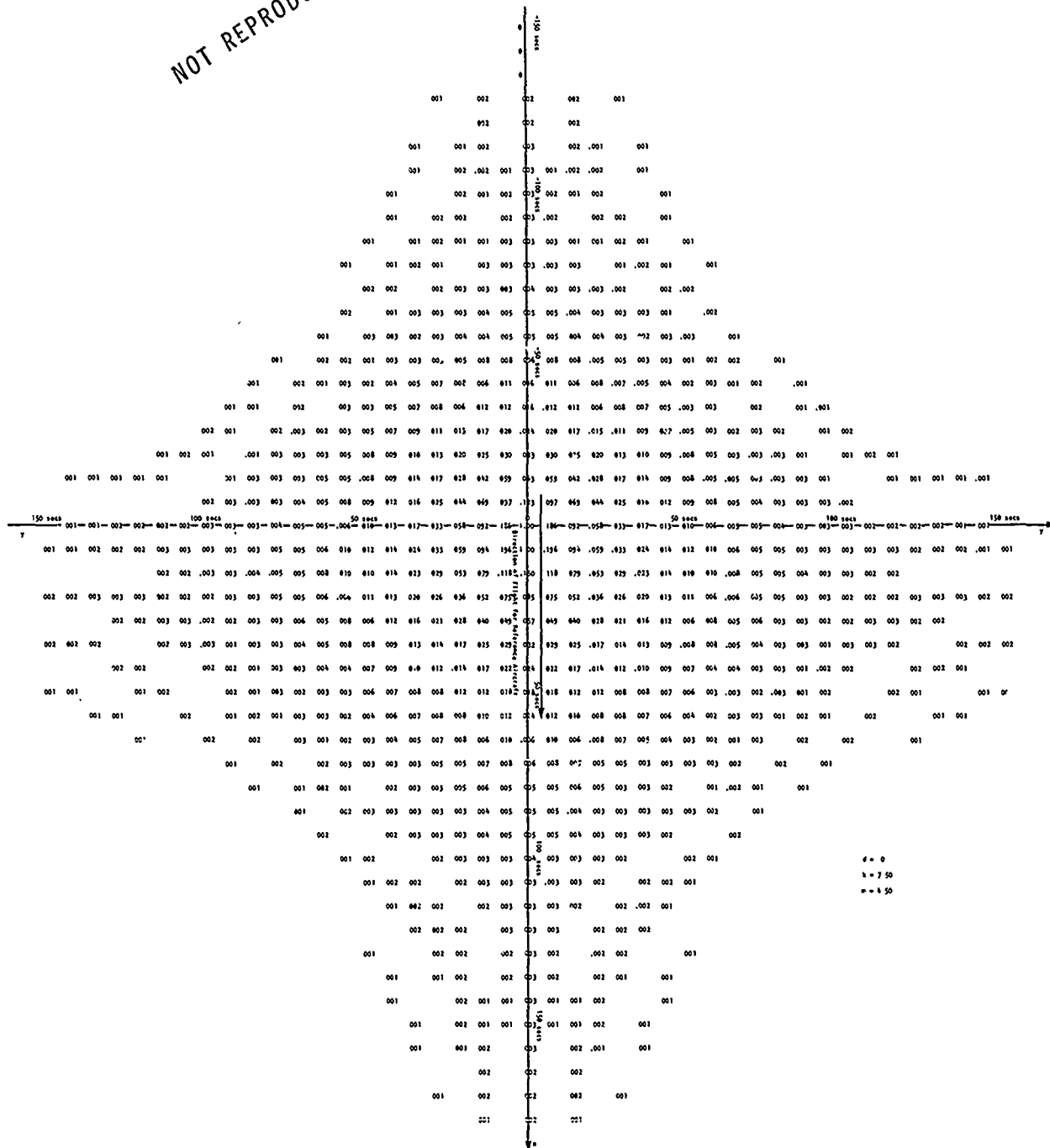


Figure 17. Probability Integral Over x-y Plane
Class 1 vs. Class 111

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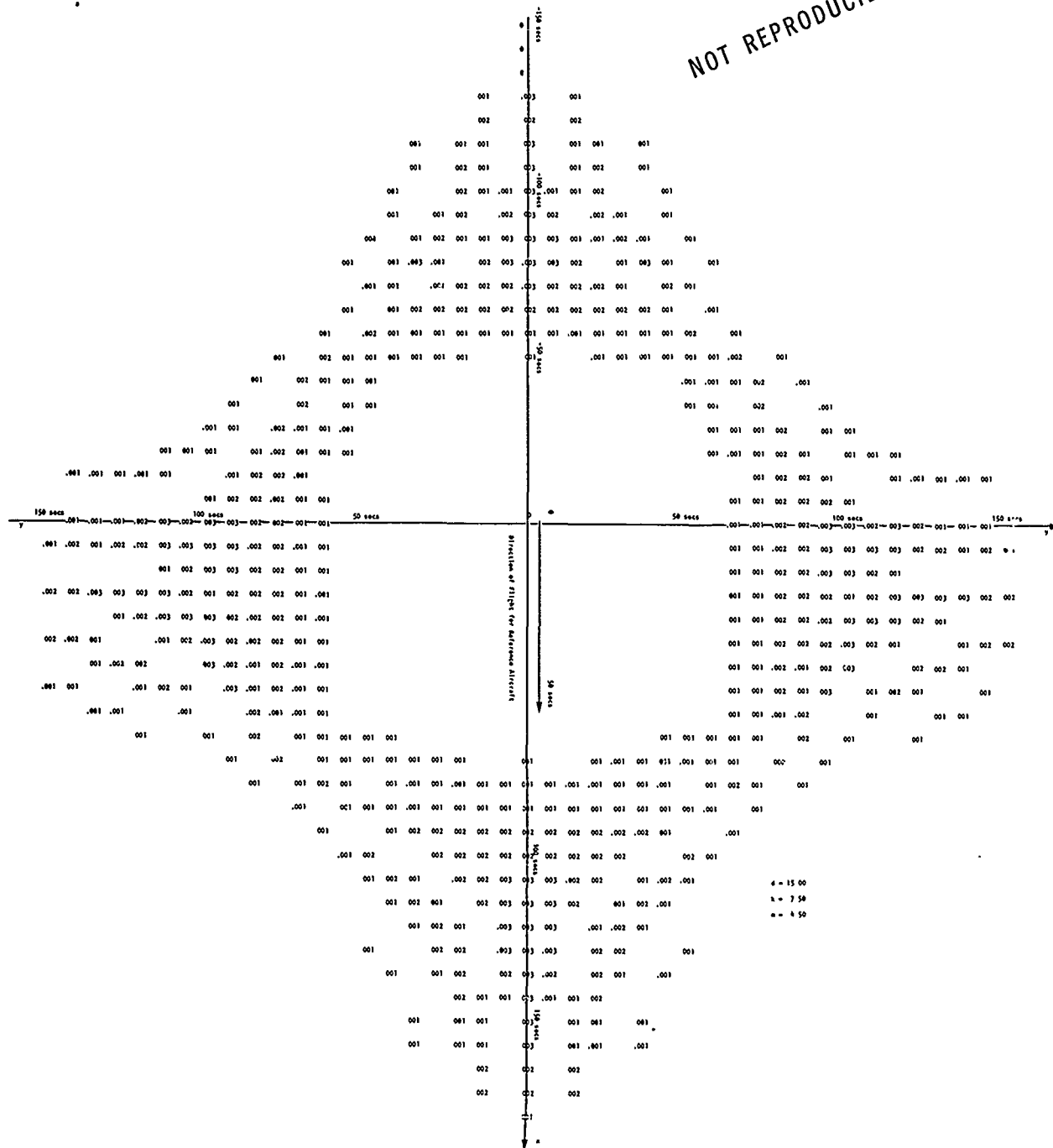


Figure 18. Probability Integral Over x-y Plane
Class 1 vs. Class 111

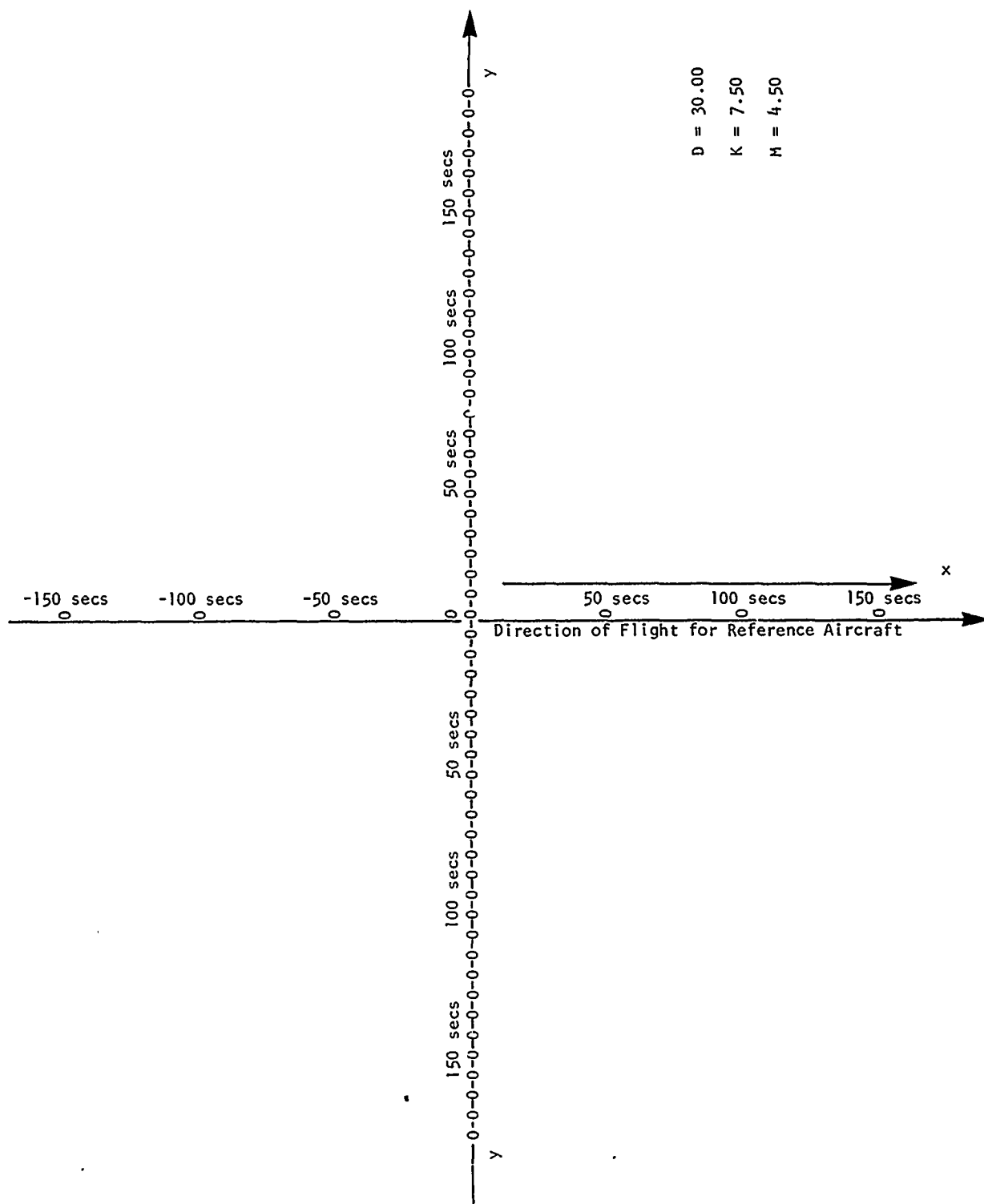


Figure 19. Probability Integral Over x-y Plane
Class 1 vs. Class 111

appearance of a pattern immediately, however, if such were the case the probabilities associated with exact solutions to Equation (9) under these conditions would be exceedingly low. The particular case shown illustrates the exaggeration of hazard conditions liable to occur in a worst case condition. The figure contains no other information and is included simply in the interest of showing all the data from the cells in Table 2.

The next nine figures (Figures 20 through 28) show the various situations which resulted when the Class II aircraft was made the reference aircraft against each other class as emerging aircraft. The first series of three figures (Figures 20, 21, and 22) shows a Class II aircraft being confronted by a Class I aircraft. Attention is immediately drawn to the relatively tiny geographic area within which the confrontation is played out as well as the relatively small areas in which there is any appreciable probability of collision even with the small d values used in the simulation. This is very encouraging in that it suggests that the two slowest classes of aircraft constitute relatively slight hazard to each other even when operating quite closely. This outcome confirms the experience around busy major terminal areas, or the situation on Sunday afternoon around the local sod field. In both cases there is often a "crowded" sky but, in actual fact, surprisingly few narrow squeaks considering the number of airplanes that are in operation at one time. Low absolute speeds plus the extra couple of hundred feet of altitude that the faster aircraft traditionally carry around the pattern could be, apparently, what is turning the trick of safety for uncontrolled VFR airports.

Figures 23, 24, and 25 show Class II aircraft intruding upon Class II reference aircraft.

Figures 26, 27, and 28 show Class II aircraft vs. Class III aircraft. Again, note the peculiar square configuration which emerges. Again, d was set at or above d_{\max} on Figure 28 and the computer drew a blank diagram.

The next nine figures (Figures 29 through 37) deal with the confrontations that occur when a Class III aircraft serves as the reference aircraft. Figures 29, 30, and 31 show Class III vs. Class I encounters. The extremely long and seemingly narrow swath of this pattern will be instantly noted. The Class I aircraft, being so relatively slow, has to be almost directly on the trajectory to get hit but, and this is important, if it is on that trajectory, it seems to have a somewhat longer area of high probability of near miss than is shown in the previous figures. (Caution should be used in geographical interpretations with these high-speed aircraft for the confrontation band, while only 4 or 5 seconds wide, is three-quarters of a mile wide in feet.)

The next three figures (Figures 32, 33, and 34) confront a Class III aircraft with a Class II aircraft with the somewhat teardrop results depicted therein.

The last three figures (Figures 35, 36, and 37) show a Class III aircraft confronting one of its own kind. Note again, these figures are very tricky. At first glance, the probabilities of contact of the near miss sphere seem quite small over most of the area and, unless it is recalled that the aircraft are making a good 880 feet/sec., the confrontation appears to take place in a

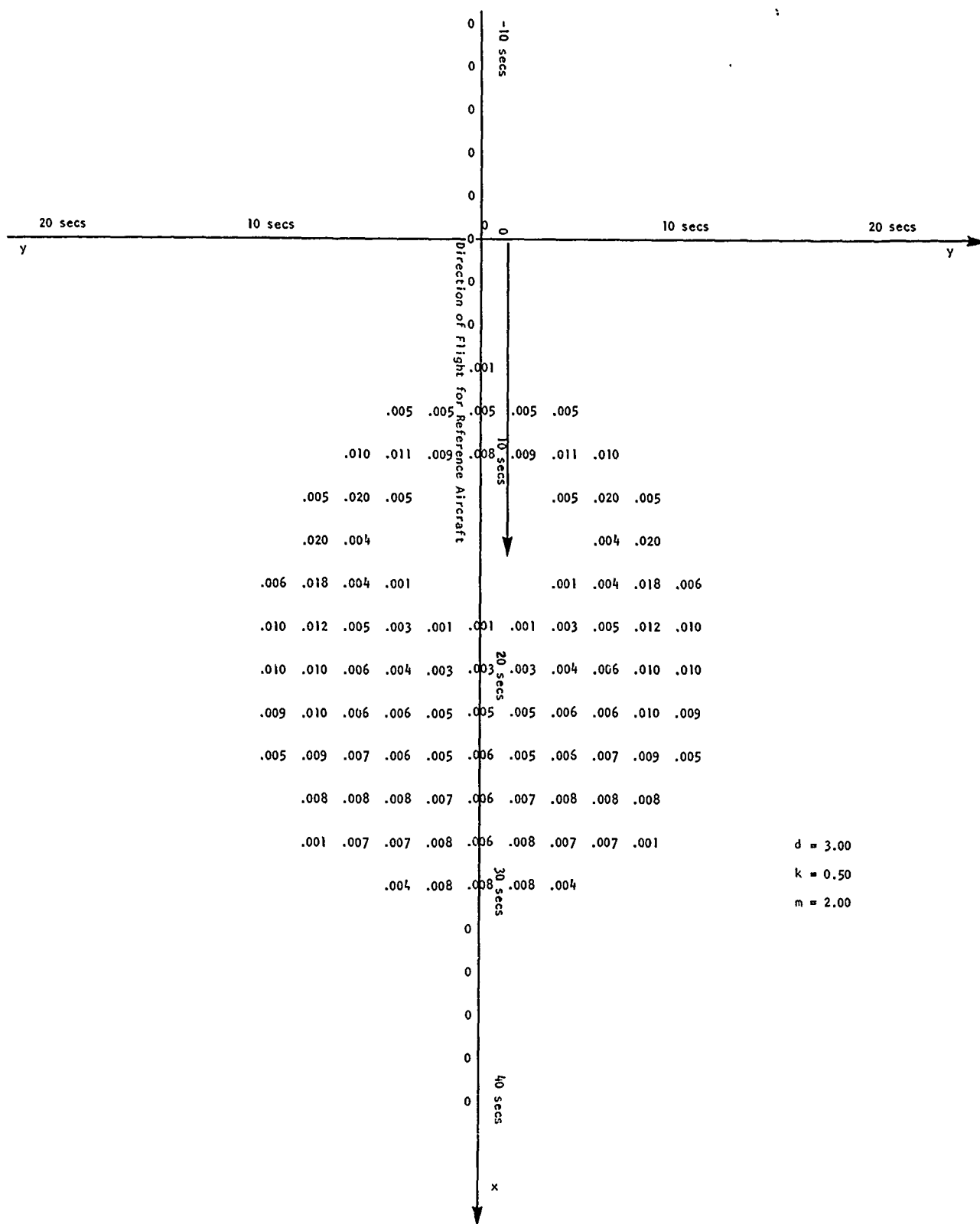
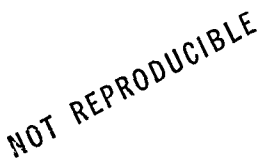


Figure 22. Probability Integral Over x-y Plane
Class 11 vs. Class 1



d = 50
k = 100
w = 200

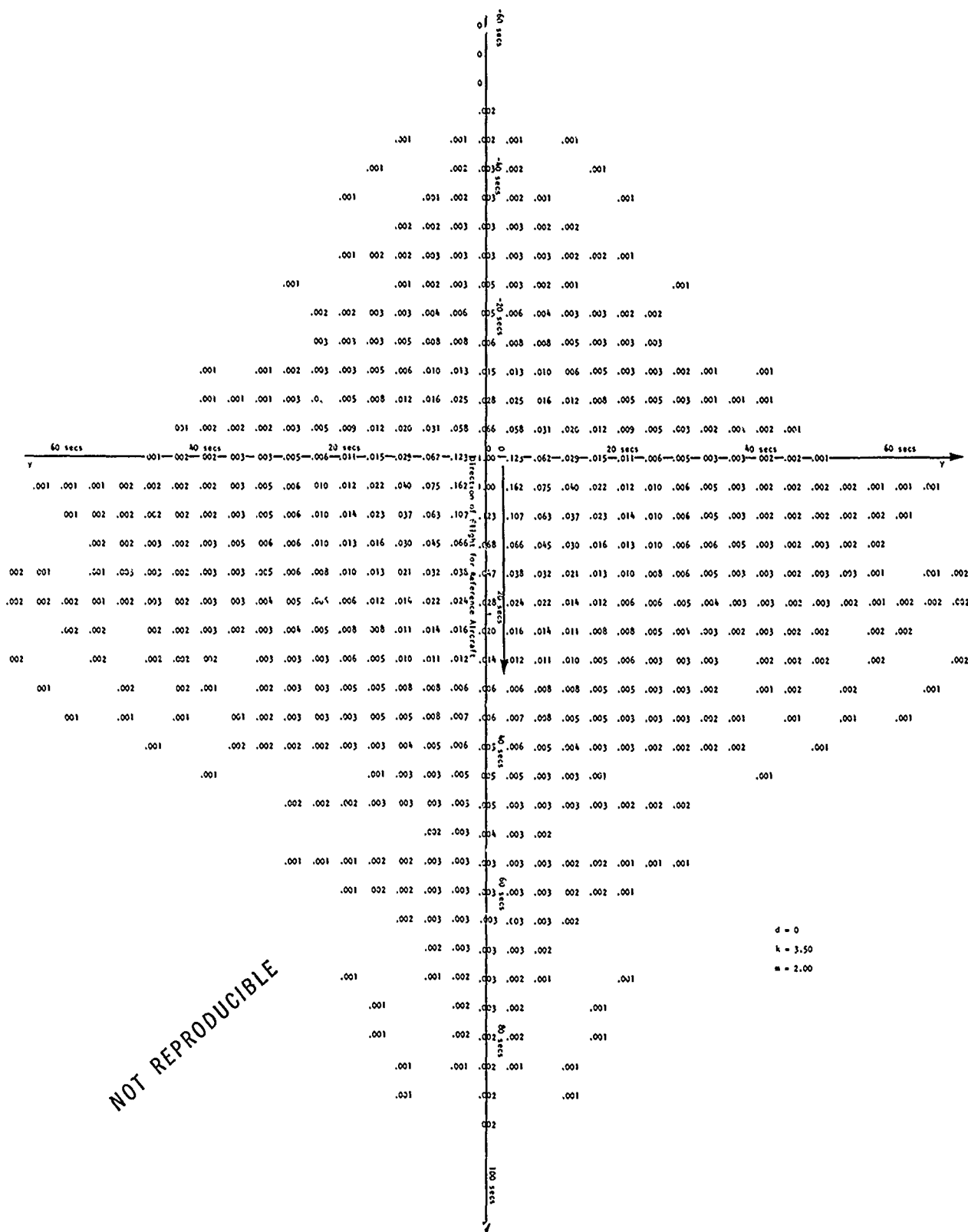


Figure 26. Probability Integral Over x-y Plane
Class 11 vs. Class 111

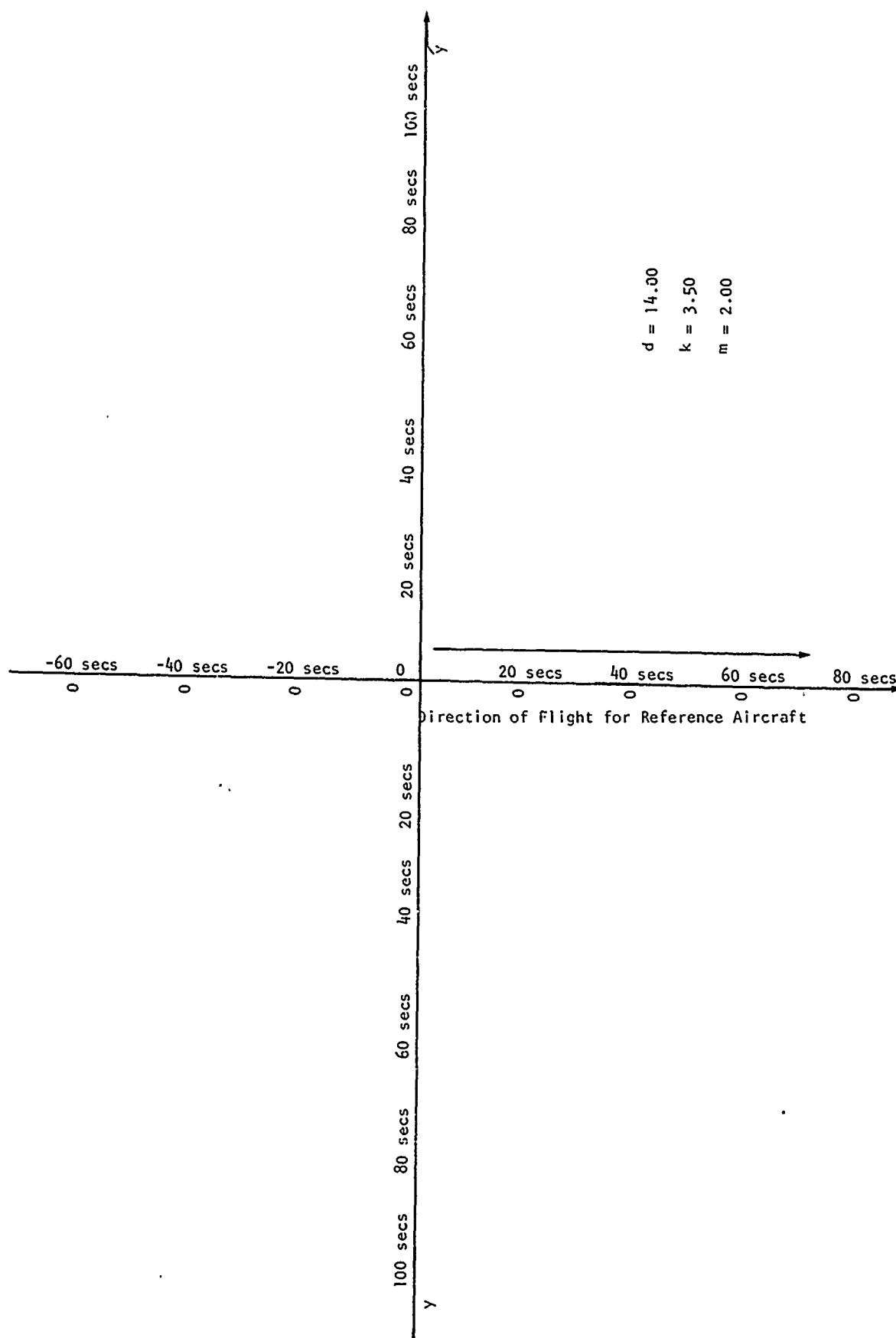


Figure 28. Probability Integral Over x-y Plane
Class 11 vs. Class 111

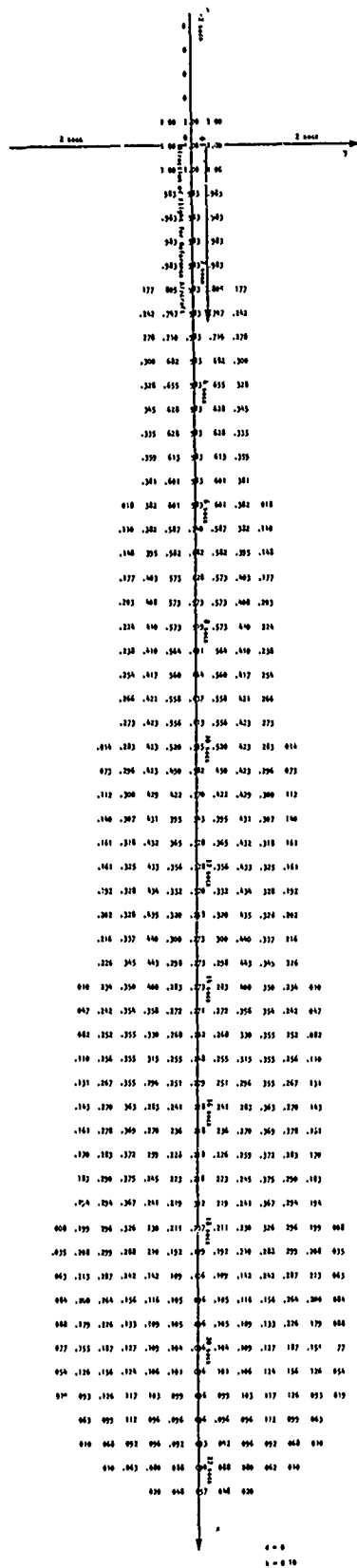


Figure 29. Probability Integral Over x-y Plane
Class 111 vs. Class 1

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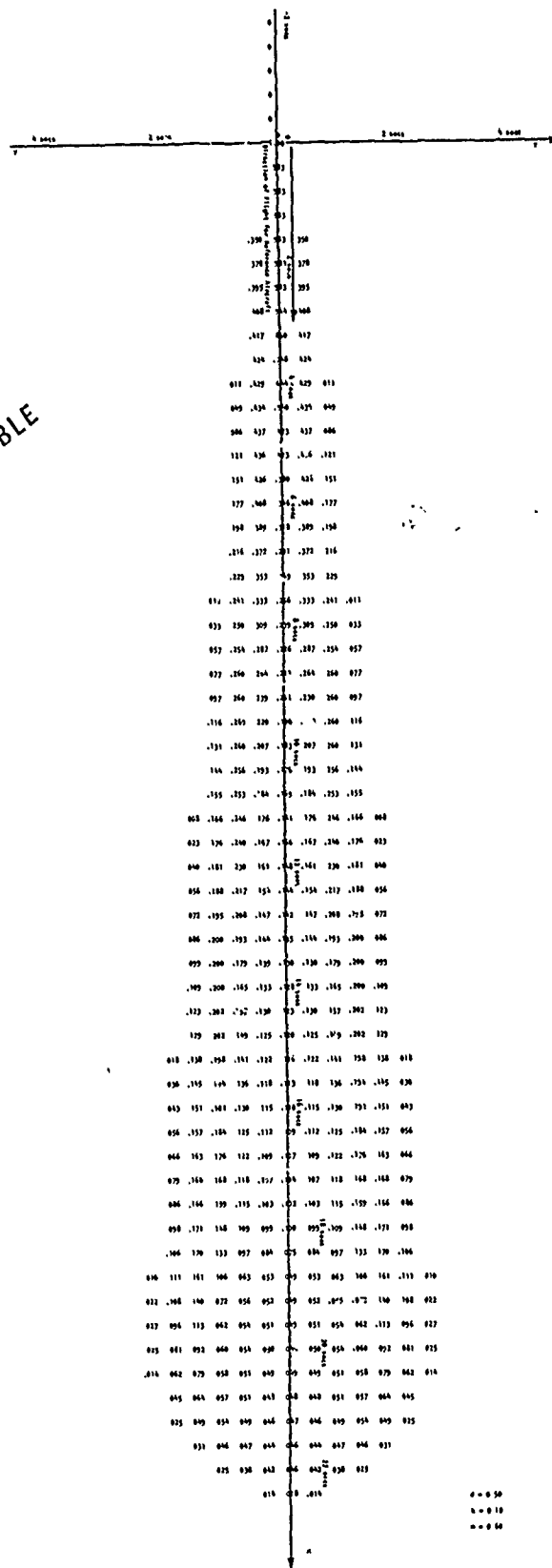


Figure 30. Probability Integral Over x-y Plane
Class 111 vs. Class 1

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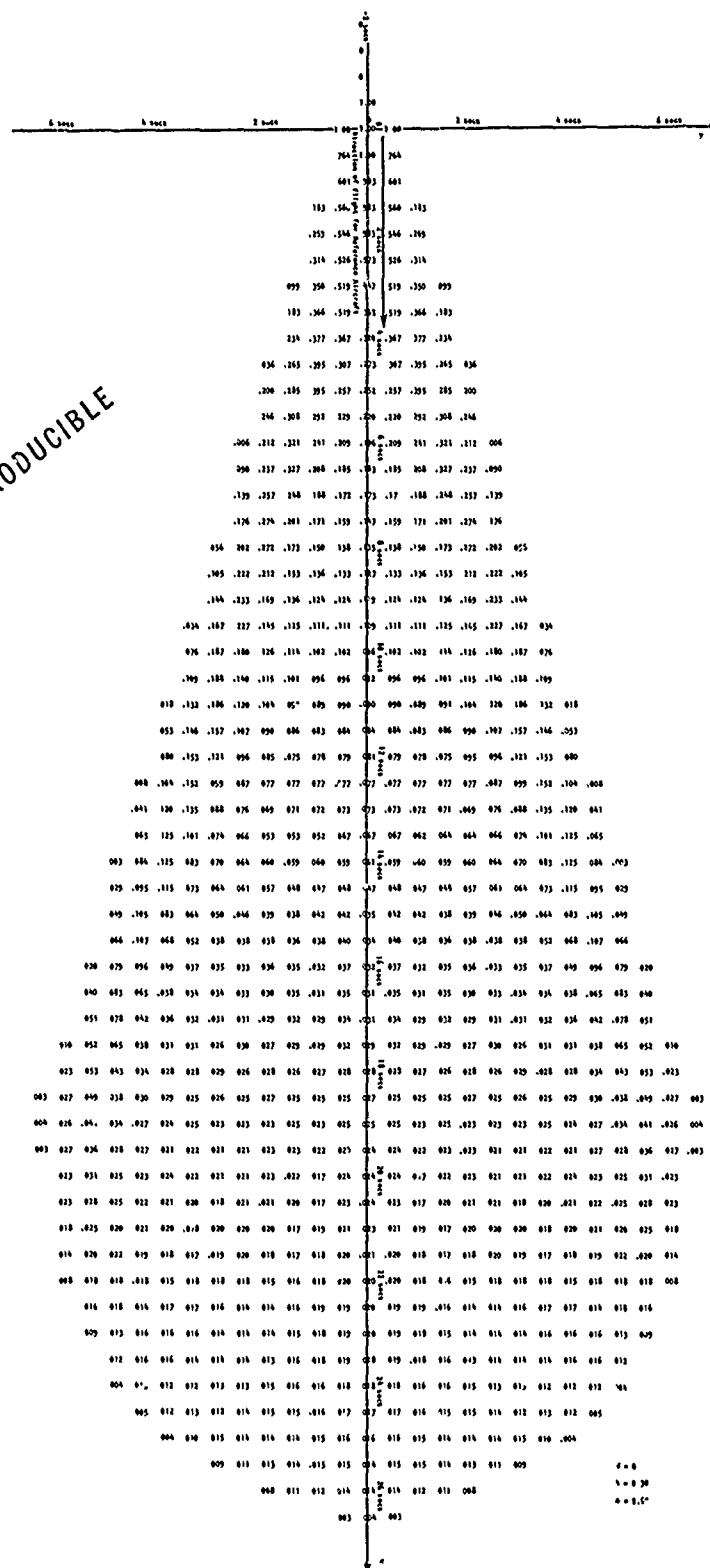


Figure 32. Probability Integral Over x-y Plane
Class 111 vs. Class 11

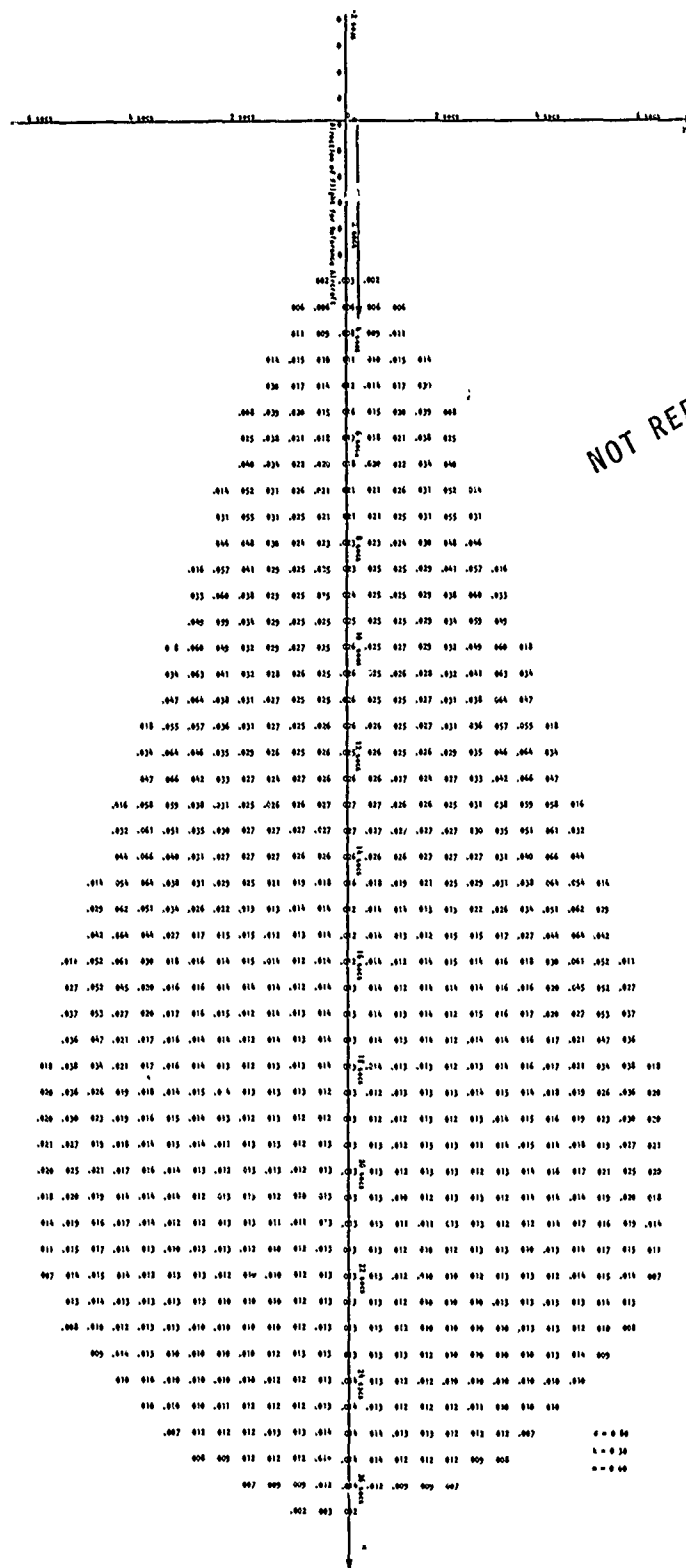


Figure 33. Probability Integral Over x-y Plane
Class 111 vs. Class 11

small area since the probability falls to zero in a very few seconds. In point of fact, the confrontation area is really *several miles across* because of the high velocities involved.

Of the many factors which become evident upon studying Figures 11 through 37, perhaps the most striking is the *enormous size of the very low probability regions* ($P < .05$). This is perhaps most noticeable in encounters of slow aircraft with the high speed Class III aircraft. The significance of this is particularly important. In the first place, when the enormous size of the airspace available for aircraft to use is considered, the possibility of another aircraft appearing at any given point is extremely remote. However, random, low probabilities for the emergence of an intruding aircraft should not be assumed. Quite to the contrary, at certain points such as along an airway, over omni stations, near the outer marker, or along the ILS, there is a concentration of aircraft. What the figures from the simulation reveal is, even if there is another aircraft fairly close by, the probability that whatever it does will cause a near miss is surprisingly, and reassuringly, low. Over very wide areas, almost any rational evasive maneuver by the reference aircraft would have a high chance of success. Thus, while there are indeed regions in which emerging aircraft can present possible hazards, the probability of aircraft emerging in these regions is low, and the probability of their actually being hazardous is even lower. Results such as these are indeed gratifying and go a long way toward explaining why aviation is as safe as it is, why certain rules of the road and certain separation standards are as effective as they are, and thus, why so few near misses actually occur.

Some of the more predictable results found in the figures pertain to the geometric shapes of the $P > 0$ boundaries. For $k \leq 1$ the boundaries lie entirely in the forward hemisphere of the reference aircraft. This is obvious since an aircraft cannot be overtaken or struck from behind by a slower aircraft. As k decreases the cone of hazard possibilities becomes narrower. The apparent narrowness of this cone suggests that the responsibility for making an avoidance maneuver should be placed on the faster aircraft, if possible; since, at first glance, it could be concluded that he can more readily maneuver his narrow hazard cone (along with his aircraft) and so place the slower aircraft outside the hazard region. However, this idea has practical limits (g forces, control effectiveness, etc.), and the illusion of speed is misleading because the "beam" of probabilities looks narrow but is actually quite wide in terms of geography. The Class III aircraft would only have to change heading by about 1 degree per second for 15 or 20 seconds to make a wide miss. That would seem to be a comfortable maneuver even for the largest or fastest aircraft. On the other hand, tests (or further simulation) might reveal that it is more effective to move the target aircraft a few feet than to try to deflect the bullet-like aircraft. Further study is clearly warranted.

In encounters with faster aircraft the slower aircraft is entirely surrounded by threat possibilities. Interestingly enough, this may be a partial explanation of why General Aviation has a somewhat less than happy safety record, and why General Aviation pilots complain that it is the faster aircraft that threaten them and not other General Aviation aircraft. It is true that many of the pilots in General Aviation are students, low-timers and Sunday pilots with reduced skill level, but it is also true that the flight

characteristics of their aircraft are such that they simply have much larger zones of probability of getting hit. For example, in encounters with aircraft just twice as fast, the degree of hazard becomes almost equally as prominent directly abeam or directly astern as it is dead ahead. Even an expert pilot can hardly protect himself by constantly looking in all directions for he still has other visual duties. In most aircraft, in fact, vision to the rear is well-nigh impossible, even if the pilot were able to devote time to looking aft.

One aspect of placing an upper limit on Γ and on the critical reaction time is the appearance of a "doughnut hole" in the $P > 0$ boundaries as the vertical separation, d , increases. This hole centers around a transition zone in ψ , the heading of the emerging aircraft. For example, for aircraft directly above or below the reference aircraft to satisfy the hazard conditions, they must be flying rather close to the same general direction as the reference aircraft ($\psi \sim 0^\circ$) and, of course, descending or ascending. For an aircraft in the distance to satisfy the hazard conditions, the aircraft must be heading rather directly toward the reference aircraft; i.e. $\psi \sim 180^\circ$. Placing a limit on Γ requires a certain period of time to elapse before the emerging aircraft can be within the near miss sphere of the reference aircraft. If the time remaining from this minimum altitude changing time to the end of the critical reaction time is too brief, the regions of $\psi \sim 0^\circ$ and $\psi \sim 180^\circ$ threats will not overlap and a hole or "safe" zone appears. Please note that this does not mean that a collision can never occur if the emerging aircraft appears in this "safe" zone; it means that in this simulation a collision will not occur in the next 20 seconds.

This particular study has not concerned itself with analysis of the influence upon vertical separation rules of exerting constraints upon the permissible rate of altitude change. However, it is evident that it is possible to *fly closer to clouds if the emerging aircraft were constrained to rather bland rates of climb or descent*. This is a very worthwhile area of investigation since it could possibly *change all that this report has concluded in the way of a vertical cloud separation rule*. If operators could live with a limitation on their altitude change rate, a different (and less stringent) set of cloud separation rules could be almost guaranteed. One very desirable rule would be a limit on descent rates so as to enable closer operations beneath cloud. This would permit operation under lower ceilings. This is a particularly noteworthy comment and deserves closest attention.

The plots in Figures 11 through 37 stimulate many thoughts and hypotheses; this is, in part, their purpose. Probably no one is more acutely aware than the researchers how limited this simulation effort has been and that it is purely elementary experimentation to see what will fall out. *Rework and extension of this effort is vigorously advocated since even this limited workup appears to have been surprisingly profitable and informative*. The comments and discussion submitted represent a few of the more obvious ideas pertinent to the present study. Careful study will reward the reader with a substantially improved appreciation of the whole midair collision and near miss problem. Numerous applications outside the scope of this present study have become apparent. These ideas will be briefly discussed in a subsequent section.

Part B - Derivation of Hazard Functions

The second portion of the computer output comprises the end product of the mathematical analysis, the hazard functions. *Beyond this point the practices involved in development of the proposed new separation standards are acknowledged to be based on the interpretation of the computer results, with a heavy blend of common sense and experience.* Perhaps a more satisfactory analytical outcome could be extended at this point if there were sufficient environmental data to derive a cost function (or, more probably, to derive a set of cost functions) and then to relegate the decision-making process to a cost-benefit scheme. In lieu of this information, however, the forthcoming reasoned approach may suffice for the present. This problem is discussed later in this report.

Before continuing with the interpretation of the computer results and an account of how the proposed separation criteria were derived therefrom, a brief report on how the hazard functions were computed is in order. The vertical degree of hazard, $H_V(d)$, and, hence, the standards for vertical separation from cloud, was computed by summing the conditional probabilities, $P_{H/P}(x, y, d)$ over half the x-y plane located at a distance, d, above the reference aircraft and multiplying this sum by the area surrounding the point at which the probability was computed, as in (26) below. (The same computation would supply the separation below cloud.)

$$(26) \quad H_V(d) = \left(\sum_{x, y} P_{H/P}(x, y, d) \right) \Delta^2$$

Although the full value of $H_V(d)$ would be twice the computed value because of the symmetry of the x-y plane, the actual computed value was used in the determination of the proposed separation standards listed later herein since the decisions were based on relative values of the hazard functions and a factor of two would not affect the results.

The proposed minimums for lateral separation from cloud were determined from the lateral degree of hazard function $H_L(y)$. This was computed by summing the conditional probabilities along the x direction at a given value of y using the d=0 surface. The summation was then multiplied by the incremental length, Δ .

$$(27) \quad H_L(y) = \left(\sum P_{H/P}(x, y, 0) \right) \Delta$$

The proposed speed vs. visibility standards (horizontal visibility rule) were derived from the radial degree of hazard function, $H_H(r)$. This function was computed on the d=0 surface by summing the conditional probabilities closest to a semicircle of radius, r. Since the probabilities were computed in an x-y grid fashion, probabilities on a radius r were approximated by the probability associated with the closest x-y pair. The summation was normalized by dividing by the number of probabilities (including $P_{H/P}=0$) summed, n_r .

$$(28) \quad H_H(r) = \frac{\sum_{n_r}^{n_r} (P_{H/P}(x, y, o))}{n_r}$$

A complete listing of the three hazard functions computed for various values of d , y , and r for all of the nine encounters appears in Table 3.

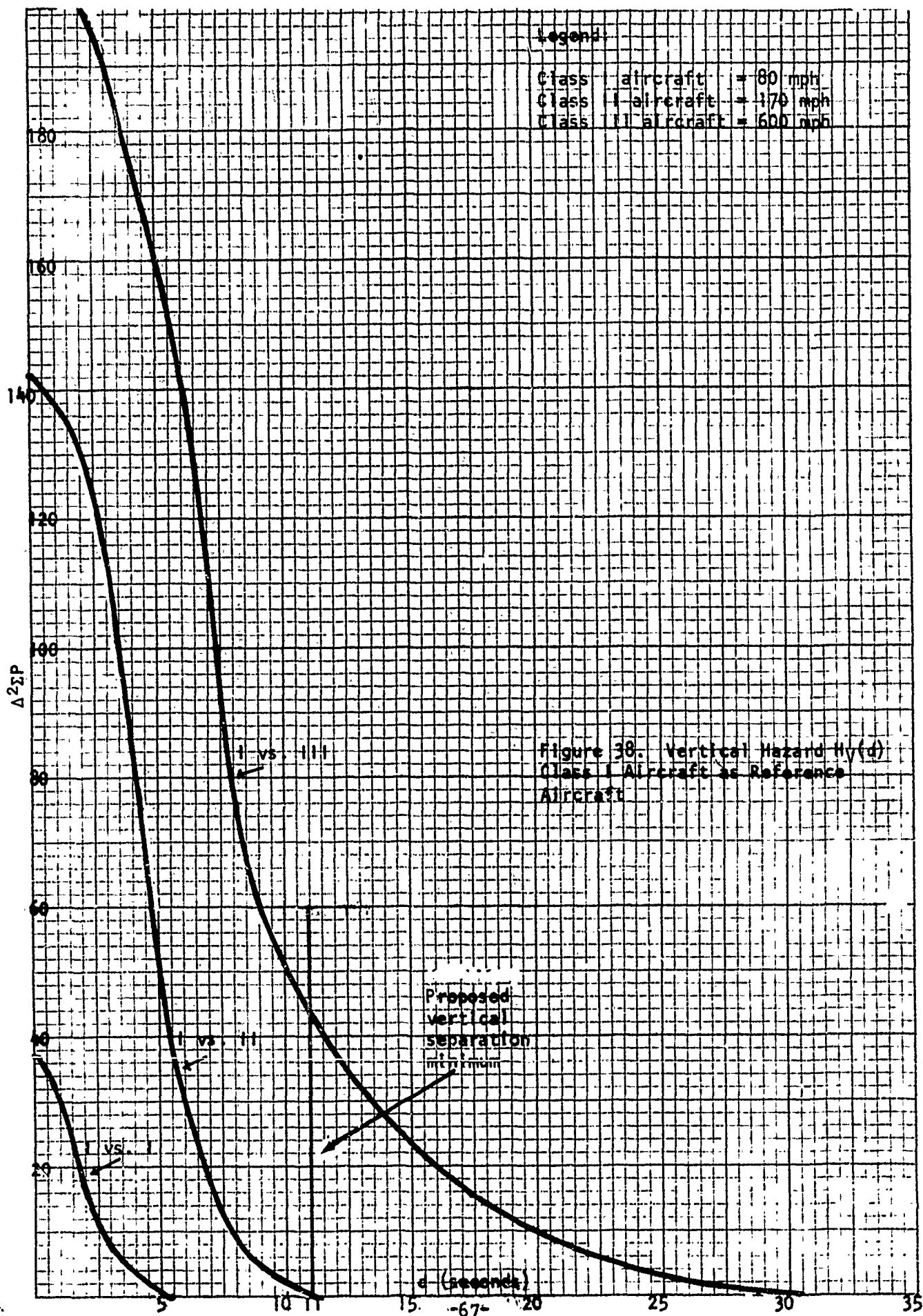
Plots of the three types of hazard functions were constructed from the data on Table 3 and are shown in Figures 38 through 46. Upon taking an overview of all these figures one finds two prominent features which develop as the separation distances increase: 1) a sharp, steep, initial fall-off in the function for all aircraft, and 2) the very slow, very gradual, tailing off from low hazard to zero hazard, which is particularly noticeable in encounters with Class III aircraft. (Circumstances associated with these phenomena were discussed earlier in connection with Figure 7.) As would appear logical, the order in which the hazard functions for each type of encounter go to zero for a given class of aircraft follows in the order of emerging aircraft velocity; that is, the hazard function for encounters with Class I aircraft always drops to zero at a shorter separation distance than encounters with Class II aircraft, and so on for Classes II and III. Notice also, in the plots of the vertical hazard functions, the least hazardous encounters at $d=0$ are between like aircraft (or when $k=1$). Encounters with either slower or faster co-planar aircraft prove more hazardous than with aircraft of the same velocity. This effect is due to the increased magnitude of the conditional probability per unit area in the case of encounters with slower aircraft and in the instance of encounters with faster aircraft the $d=0$ vertical hazard increases because of an increased area of non-zero probabilities.

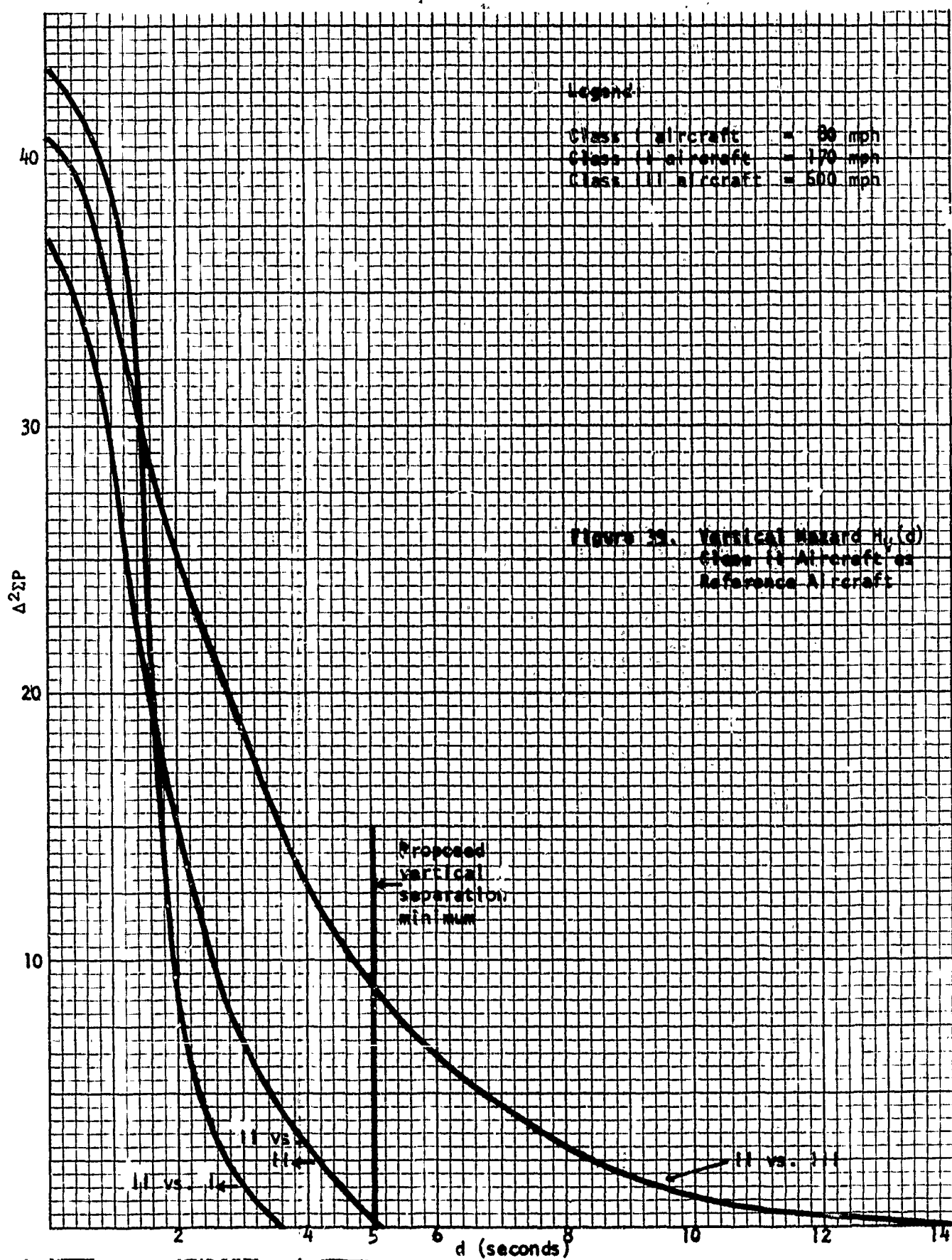
Some skepticism must be expressed here of the ability to derive such accurate and smooth curves from so few data points, but these points are the only ones available from such a limited study. This issue has received substantial consideration and it is believed that the curves are essentially correct in concept, if not in detail or degree. It is doubtful that further refinement would do more than alter the detail of some of the subsequent conclusions. It is confidently believed that the general character of the recommendations will prove correct and would survive a repetition and re-analysis with more complete computation.

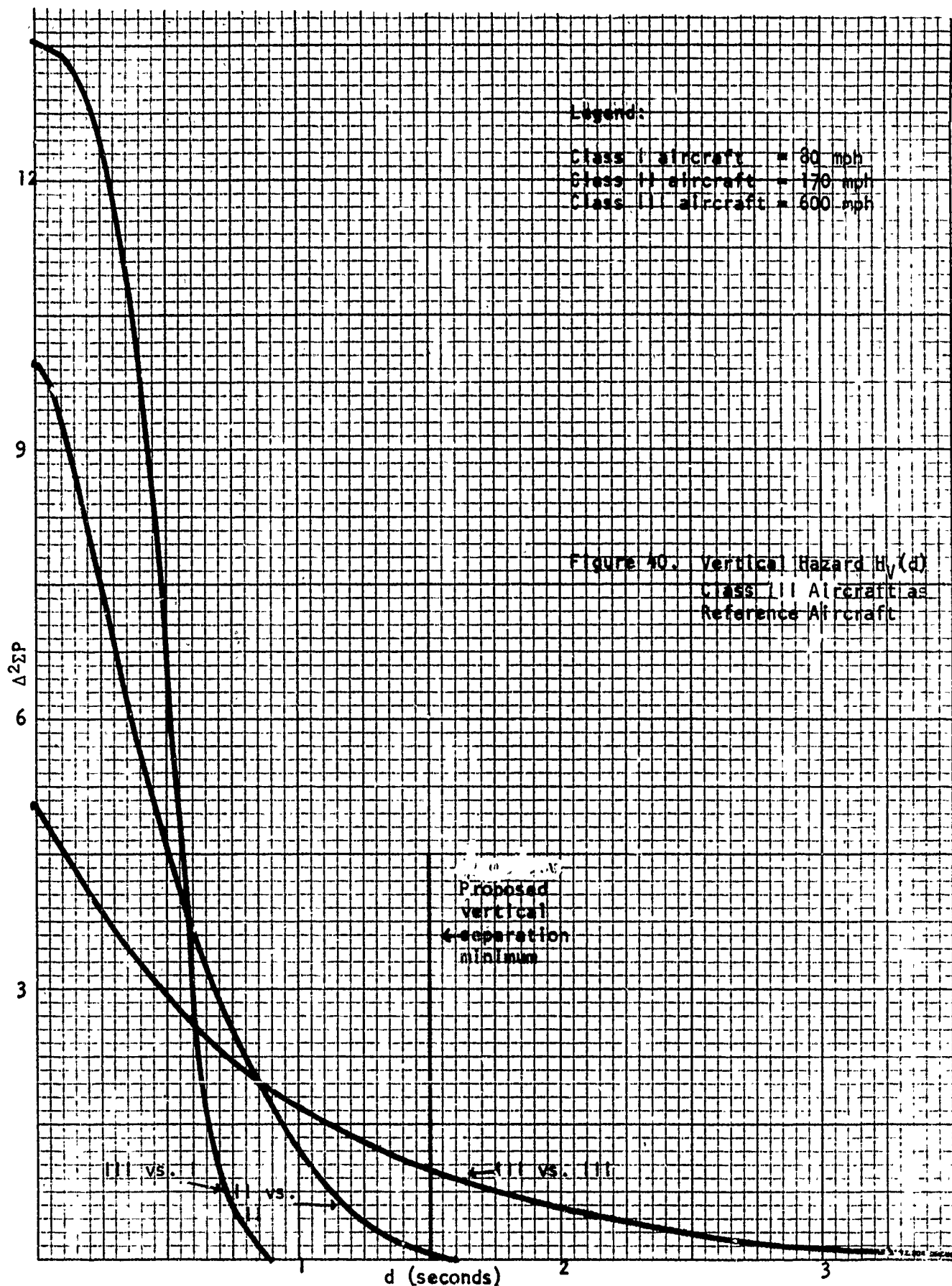
With the preparation of Figures 38 through 46, it is believed that the groundwork has been laid for a supportable set of proposed separation standards and it is to that issue that this report is next directed.

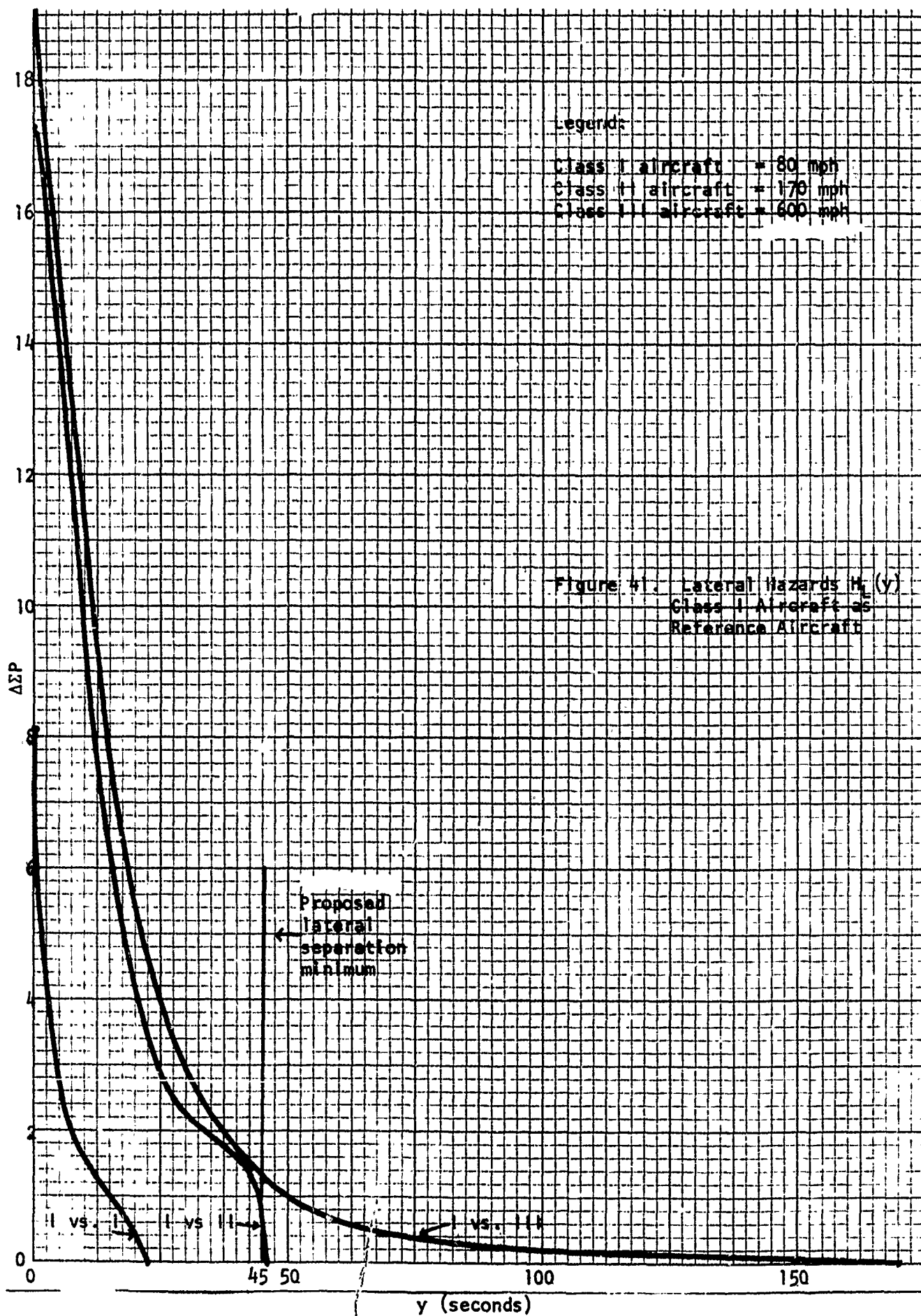
TABLE 3. SUMMARY OF HAZARD FUNCTIONS

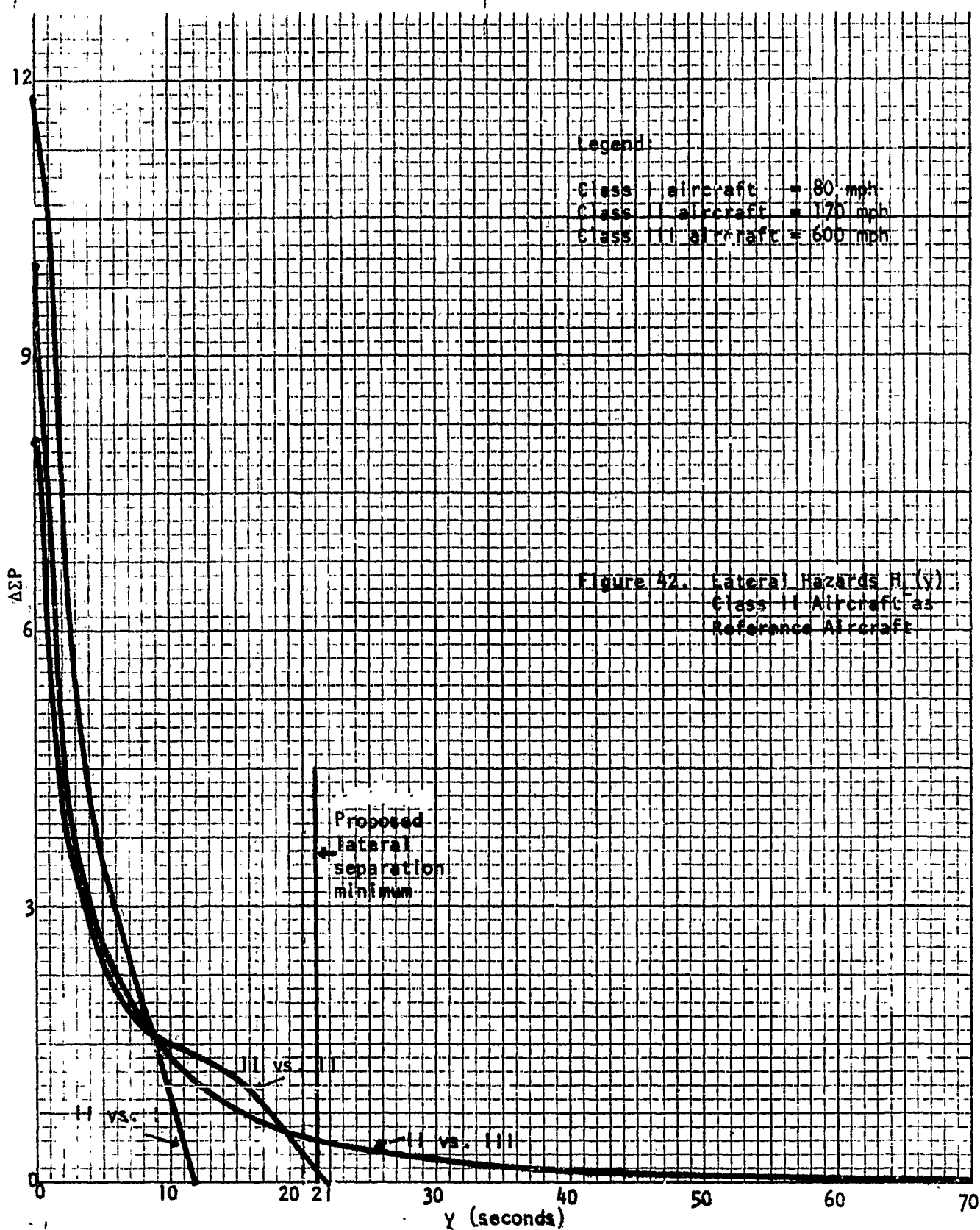
Aircraft Confrontation Type	$H_V(d)$ Vertical Hazard		$H_L(d)$ Lateral Hazard		$H_H(d)$ Visibility	$\frac{\Sigma P}{n_r}$
	d (seconds)	$\Delta^2 \Sigma P$	y (seconds)	$\Delta \Sigma P$	r (seconds)	
I vs. I	0.0	37.00	0.0	8.12	10.0	.0744
	3.0	7.08	10.0	1.47	20.0	.0167
	5.0	0.19	15.0	1.12	30.0	.0082
	5.5	0.00	20.0	0.32	42.0	.0000
			22.0	0.00		
I vs. II	0.0	141.96	0.0	17.24	20.0	.0680
	5.0	54.04	20.0	4.33	40.0	.0239
	10.0	1.84	30.0	2.16	60.0	.0098
	11.5	0.00	40.0	1.65	66.0	.0000
			46.0	0.00		
I vs. III	0.0	206.29	0.0	19.24	28.0	.0478
	15.0	23.03	50.0	0.88	50.0	.0135
	30.0	0.00	100.0	0.17	100.0	.0017
	30.7	0.00	150.0	0.05	185.0	.0000
			170.0	0.00		
II vs. I	0.0	43.12	0.0	11.82	8.0	.0955
	1.5	29.24	2.0	7.90	14.0	.0432
	3.0	1.48	6.0	2.92	20.0	.0210
	3.7	0.00	10.0	0.76	32.0	.0000
			12.0	0.00		
II vs. II	0.0	37.00	0.0	8.12	10.0	.0744
	3.0	7.08	10.0	1.47	20.0	.0167
	5.0	0.19	15.0	1.12	30.0	.0082
	5.5	0.00	20.0	0.32	42.0	.0000
			22.0	0.00		
II vs. III	0.0	40.96	0.0	9.99	12.0	.0364
	7.0	4.80	20.0	0.46	32.0	.00465
	14.0	0.00	40.0	0.10	56.0	.00069
	14.2	0.00	60.0	0.03	92.0	.00000
			72.0	0.00		
III vs. I	0.0	13.55	0.0	11.51	3.2	.0942
	0.5	7.13	0.4	10.56	12.0	.0235
	0.8	0.31	1.2	4.20	20.0	.0070
	0.9	0.00	2.0	0.11	22.8	.0000
			2.8	0.00		
III vs. II	0.0	9.93	0.0	2.45	10.0	.0360
	0.8	2.27	2.0	1.75	15.0	.0142
	1.5	0.03	4.0	0.66	20.0	.0056
	1.6	0.00	6.0	0.10	27.0	.0000
			7.0	0.00		
III vs. III	0.0	5.01	0.0	2.16	5.0	.0214
	2.0	0.51	5.0	0.25	15.0	.00188
	3.7	0.01	10.0	0.05	25.0	.00035
	4.1	0.00	15.0	0.02	41.0	.00000
			21.0	0.00		

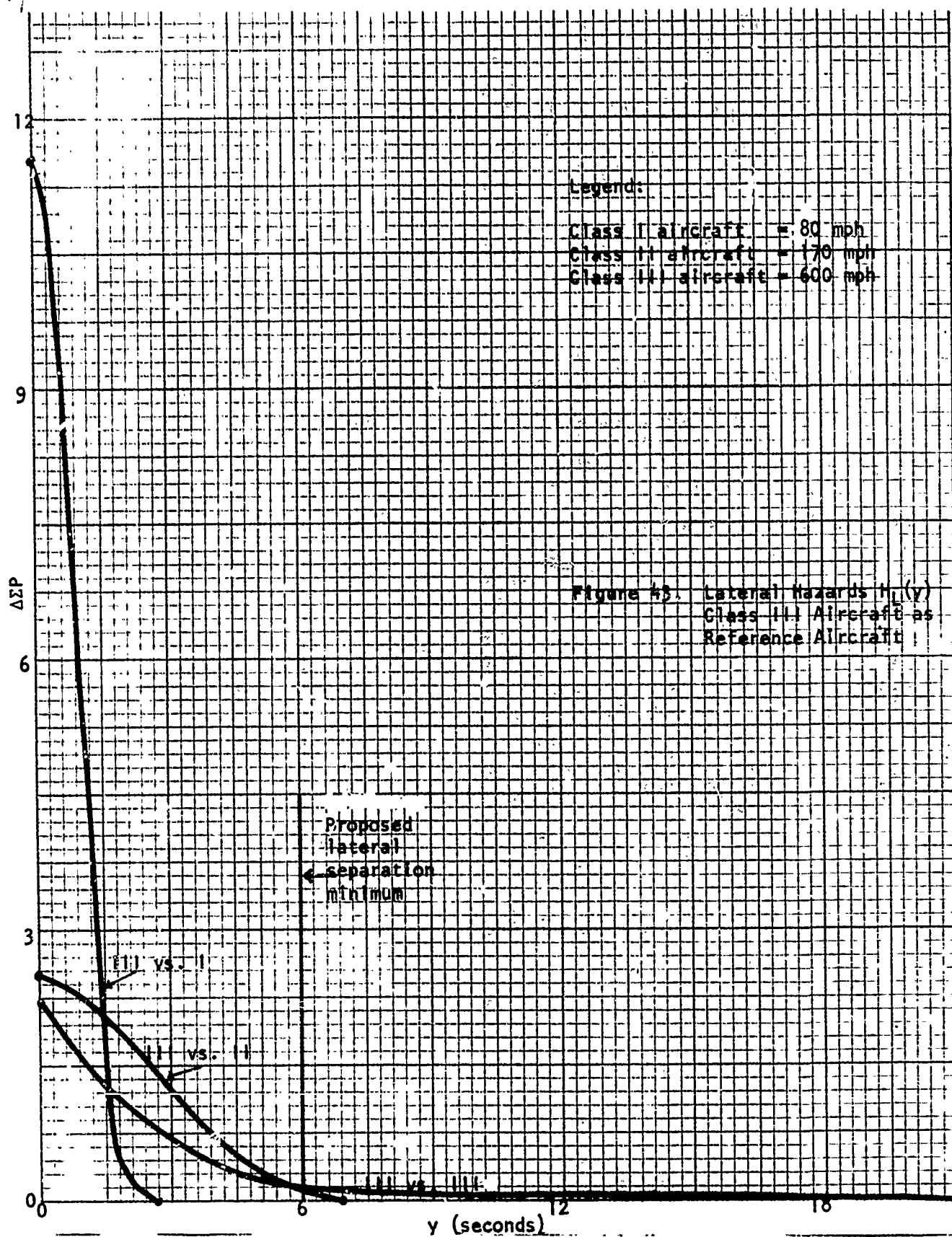


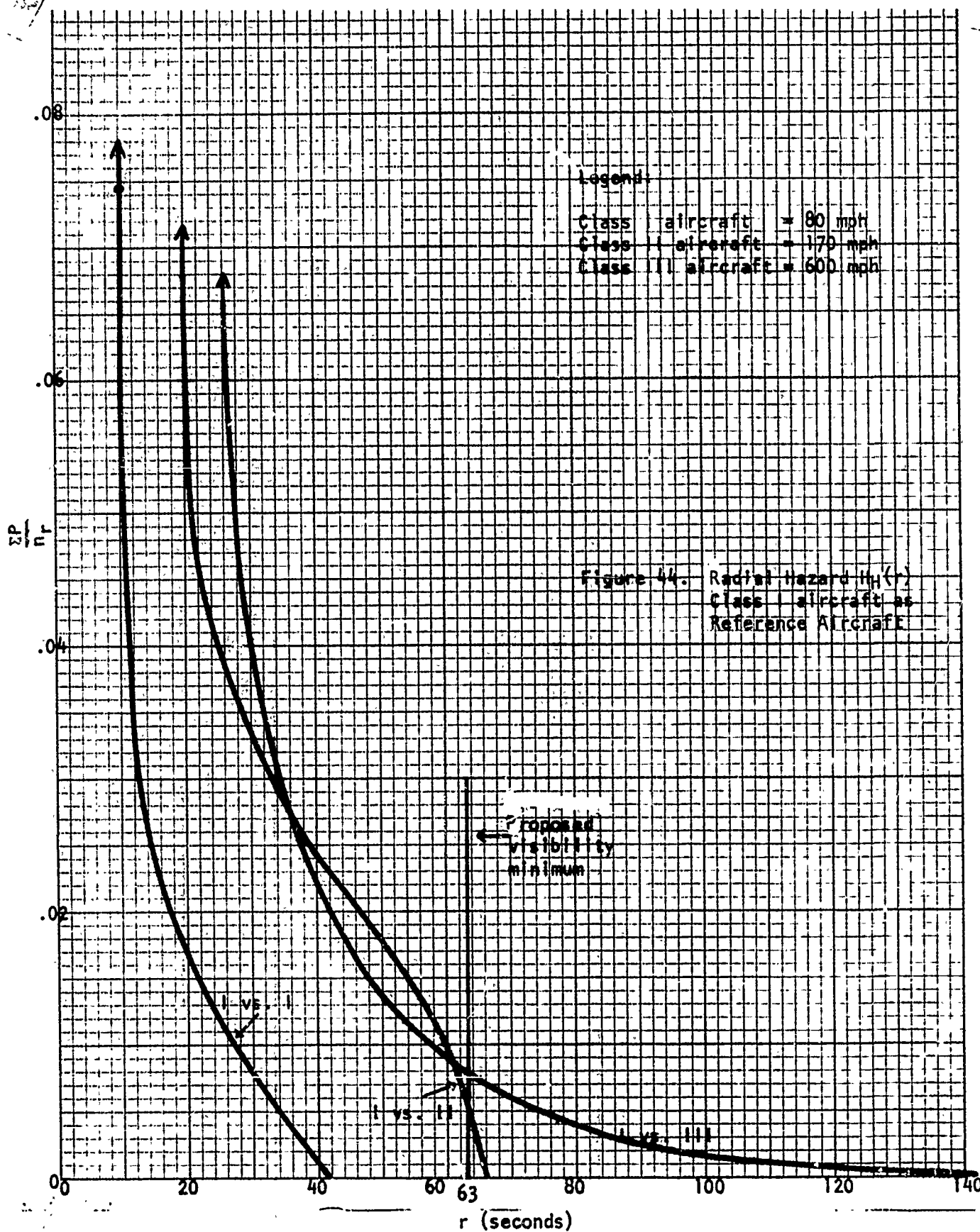


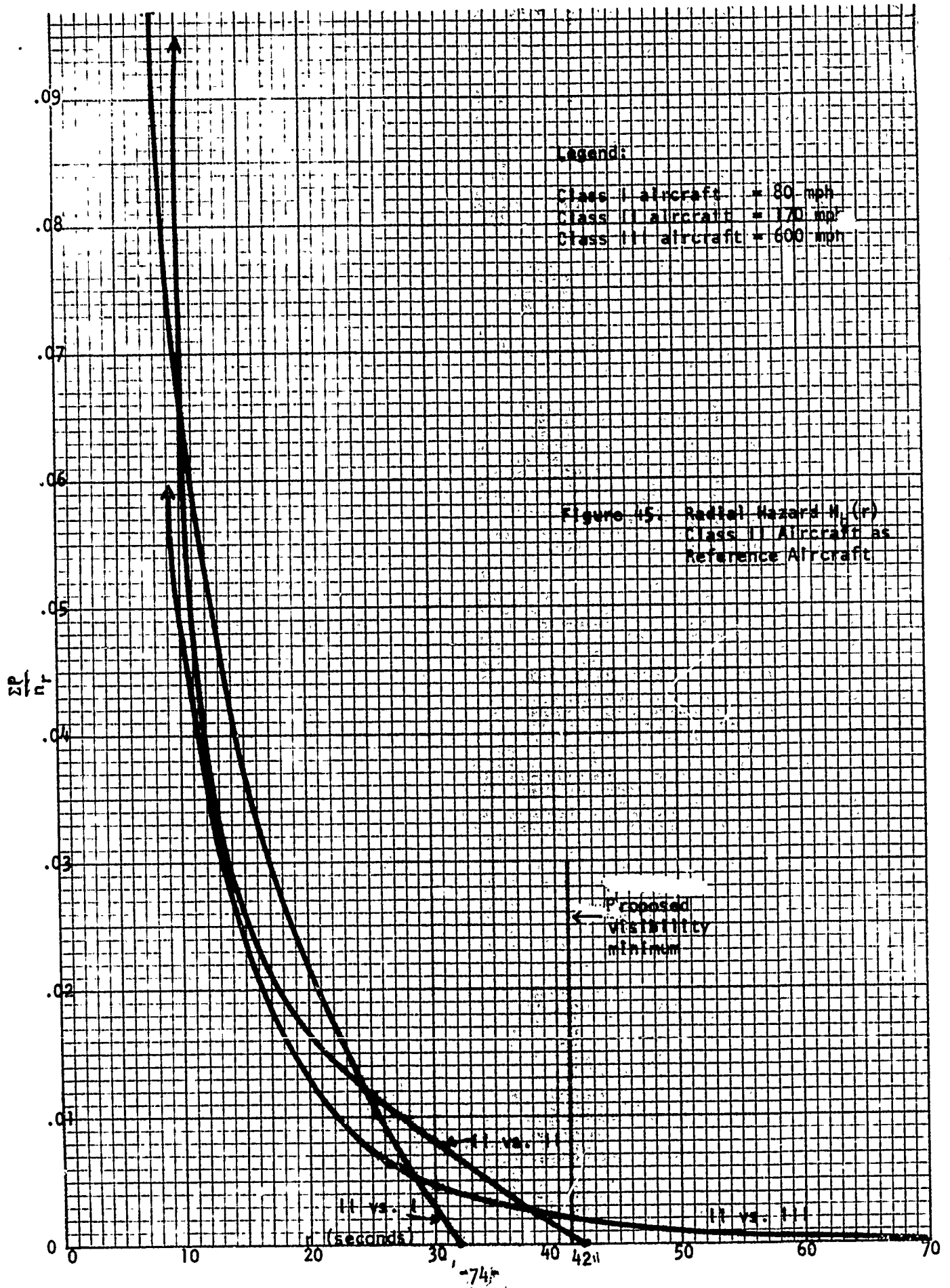


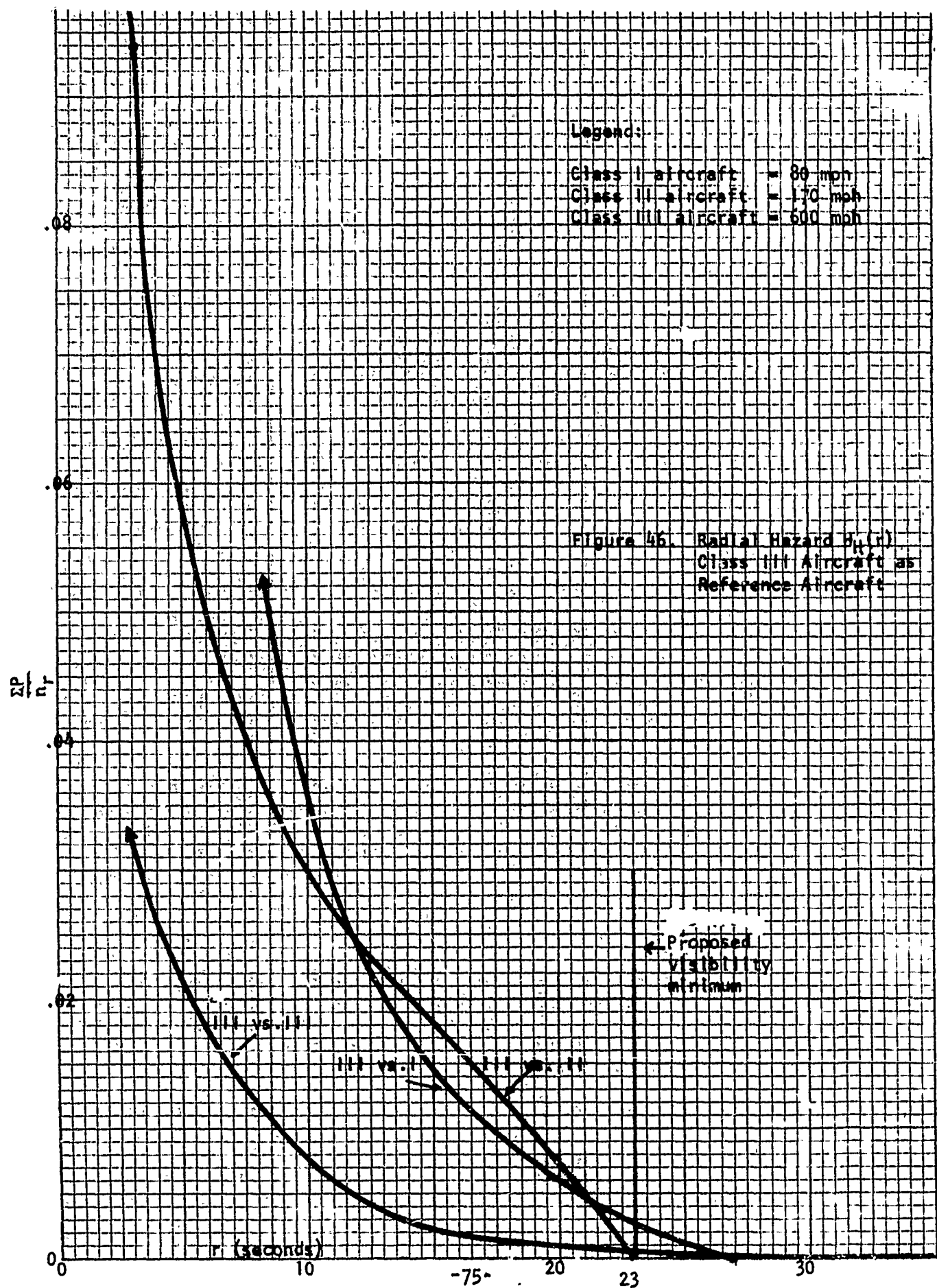












Part C - Derivation of Proposed Separation Rules

As already stated, in the absence of more extensive environmental data and an accurate cost function, the selection of separation standards has been based largely on intuitive reasoning and experience. However, the "degree of hazard" functions are now incorporated as new tools for achieving a decision. The basic objective in this decision-making process has been to insure the greatest degree of safety possible through minimizing the potential number of encounters and, at the same time, keeping a realistic view of the restrictiveness of the standards which were emerging from this analysis.

Approximately 83 per cent of all certified aircraft cruise at, or less than, 200 mph. (14, 16) These are the aircraft most likely to be engaged in VFR flight and in VFR-IFR mixing. Most light aircraft operate on VFR rules and at altitudes below 10,000 feet. Most clouds are below 10,000 feet. IFR traffic below 10,000 feet is generally required to keep under 250 knots. Much of the traffic above 10,000 feet is IFR. All these facts combined seem to support the assertion that most mixed traffic and most VFR traffic is low (10,000 feet or less) and slow (200 mph or less). Apparently, therefore, the greatest protection resulting from VFR flight rules can be afforded by choosing the separation standards such that the hazard functions for encounters with Class I and Class II aircraft are at more or less of a minimum. The relative infrequency of VFR or VFR/IFR encounters with high speed aircraft while that high speed aircraft is actually operating at high speed, and the relatively small gain in safety in such encounters for large increases in separation standards, suggests that more would probably be lost than gained by further increasing the separation minimums for encounters with Class III aircraft. Even with Class III aircraft as the reference aircraft, only a minimal amount can be gained by extending the separation minimums past the point at which the hazard function for encounters with Class II aircraft goes to zero.

It is noted that the lateral hazard (here being used as a representation of the case where an emerging aircraft emerges from the side of the reference aircraft at the same altitude as if coming from around a cloud, or out of the side of a cloud, and the radial hazard (where the emerging aircraft can come from any direction at the same altitude) are related. In general, the radial hazard presents the worst hazard and would require the largest horizontal clear space to protect the reference aircraft (largely because of the elongation along the x axis). However, to take care of the case where a reference aircraft is flying parallel to a line of cloud on one side and clear sky on the other side (as when flying parallel to a sharply defined stratus deck or coastal fog) we have defined the lateral hazard case. In actuality, and as shown in Figure 47, the real-life situation in the case of operations at the level of scattered clouds is something of a compromise between the lateral hazard and radial hazard.

In Figure 47 the Reference Aircraft is assumed to be maintaining the prescribed standoff distance from both Cloud 1 and Cloud 2. It also has the necessary forward visibility. The lateral hazard limit against Emerging Aircraft #1 is assumed to be such that they will be able to avoid each other. Emerging Aircraft #2 is also maintaining the necessary standoff distance from

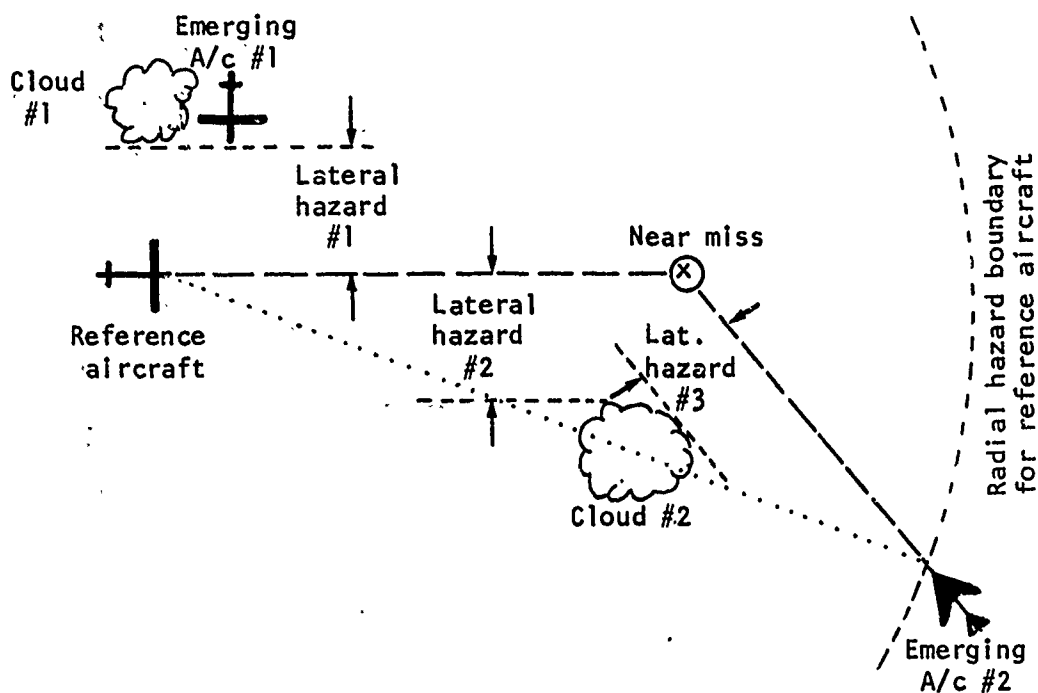


Figure 47. Lateral Hazard vs. Radial Hazard
in Operation near Scattered Clouds

Cloud #2 (Lateral Hazard #3). However, since the radial hazard concept envisages aircraft which can emerge from anywhere, it may not be sufficient to completely rely on the lateral hazard concept alone for protection. Thus, the separation shown in Figure 47 may very likely prove inadequate to protect the Reference Aircraft from Emerging Aircraft #2, even though both are "legal" with respect to cloud separation and both have the necessary forward visibility. On the other hand, the radial hazard is always larger than the lateral hazard and, if the radial hazard is adopted as the criterion, then the Reference Aircraft could not even be in the air since Cloud #2 would have to be at least as far away as the radial hazard line. This would probably be regarded as an overprotective rule. As a result, a compromise of sorts has been made. The lateral rule, as devised, protects rather well against aircraft which emerge from the side, and the horizontal visibility rule proposed takes care of most radial hazards. But, as Figure 47 shows, near misses can still occur. Furthermore, other examples of such breakdown in protection could be demonstrated.

Returning to the derivation of the rules, the selection criterion for choosing the separation and visibility standard for each class of aircraft is the following: *the proposed cloud separation and horizontal visibility standards are determined for a given class of aircraft from their respective hazard functions by selecting the separation value at which the hazard function for encounters with Class II aircraft approaches zero.*

To see how this works, refer to Figures 38 through 46 where there will be found a vertical boundary line entitled "Proposed ... Minimum." It will be noted that this line generally comes to rest at almost exactly the spot where the hazard to the Class II aircraft reaches zero. (Class I aircraft hazard level has invariably reached zero much sooner.) Thus, the only hazard of any consequence which still remains is that invoked by the Class III aircraft. Even that hazard is usually fairly small since, in most cases, the curve is already beginning to asymptote by the time it passes the chosen boundary. This seems to be a reasonably defensible, reasonably clear-cut, and mutually agreeable criterion point by which to define, even quantify, the hazard boundary.

Adoption of this procedure usually results in confrontations between Class I aircraft and Class II aircraft being almost, if not totally, impossible, with near misses between Class II and Class II aircraft occurring only a negligible portion of the time. There does continue to be a small hazard with Class III aircraft both to themselves and to other classes.

The confrontation with Class III aircraft could be brought under immediate control by causing Class III aircraft to behave as Class II aircraft when in the vicinity of clouds or when visibility is less than stated in the rule given later in this report. It is recognized that operators of Class III aircraft might reasonably be loath to sacrifice their performance capability at any time. However, it is believed that it may also be reasonable to suggest that Class III aircraft be caused to operate in domains to the left of the specified minimums of Figures 38 through 46 during such time as they are below some arbitrary altitude level, such as 10,000 feet, or some other mutually agreeable level, and operating in the vicinity of cloud or reduced visibility. It is fully understood that ~~any~~ slowing down and decreasing the rate of altitude change might not necessarily produce reduced hazards for Class III aircraft. It is conceivable that conditions of load or other operating constraints would make it impossible, or undesirable, for the Class III aircraft to attempt to maneuver at these speeds. Conceivably, attempts to operate at such slow speeds could force these aircraft to assume flight altitudes of such nose-high position, in order to maintain slow flight, that their crews could not see along their actual trajectory well enough to avoid the near miss that they would now have time to detect. It may be that range and payload considerations required to achieve economic or competitive schedules mitigate against making marginal operations, and the practical necessities of actual commercial and military operations are recognized. These factors, along with many, many others, are all perfectly reasonable and practical reasons for acceptance of certain relatively small risks by exposing Class III aircraft to acceptable levels of probabilities of near miss in return for certain benefits. (After all, this definition of a "near miss" is substantially different from an actual collision.)

In an attempt to spread the burden equally among all airspace users, and somewhat in return for the speed control and altitude rate change control changes implied elsewhere herein for Class III aircraft, somewhat rougher requirements than are presently in effect for horizontal and vertical separation from clouds and VFR visibility minimums are suggested. These would, doubtless, work some hardship on the General Aviator but would certainly repay him with improved near miss experience, especially against the higher

performance aircraft which have also been asked to endure somewhat of a penalty. Collectively, with each class of operator giving away a little, all of them will gain a substantial amount in return.

The full assessment of all these possibilities lies outside the scope of the present work, but they definitely should not remain unconsidered. Indeed, further study is vigorously urged along the lines of getting all the cost-benefit factors defined and discussed before rule changes are made.

Using the criteria outlined above, the resulting proposed standards, indicated on Figures 38 through 46, are listed by aircraft class in Table 4. The influence of operating at certain hypothetical maximum and minimum velocities for aircraft of each class are also entered on Table 4. These hypothetical values might represent economy cruise, normal cruise, and fast cruise for these classes of aircraft. In order to assist the reader in visualizing the circumstances at play in each example, the conversion of the separation standards from seconds to distances and the range of distances for a given class are also provided. In extending the class range to maximum and minimum velocity values it must be realized that the value of m (in seconds) has remained fixed and not the value of M (in feet). The net result is to increase or decrease M (in feet) as the velocity varies through the class. Thus, a Class I aircraft ($m = 4.5$ sec when opposite Class II aircraft) of airspeed equal to 88 ft/sec has a near miss sphere of 396 feet, while one at 147 ft/sec has a near miss sphere of 761 feet. This linear variation may not be entirely justified; in fact, in the faster class of aircraft the value of m was reduced to bring the near miss radius within acceptable bounds. If a Class I aircraft were to maintain a fixed near miss radius in terms of feet, then ideally the problem should be rerun at the velocity extremes shown in Table 4, adjusting m accordingly. Since this luxury was not available, Figures 48A/B were plotted to illustrate graphically the variation involved in a worse case, i.e., where m remains fixed and M varies.

1. Vertical Separation Standard

A rule for the vertical separation above or below cloud should possess a number of features, some of which are listed:

- a. Provision of a reasonable degree of protection to both of the confronting aircraft regardless of their respective characteristics (speed, heading), and not protect one while unduly restricting the other;
- b. Offer the emerging aircraft pilot enough time to look around when he pops out into the clear and not necessarily impose the entire burden of detection and reaction upon the aircraft already operating in the clear;
- c. Some simple distance that pilots can probably estimate reasonably correctly most of the time, but which is large enough that if they either inadvertently underestimate or deliberately "bend" the rule a little, there will still be a reasonable degree of protection for both aircraft;

TABLE 4. RANGE OF SEPARATION DISTANCES FOR FIXED SEPARATION TIMES

Aircraft Class	Assumed Velocity		Vertical Separation		Horizontal Separation		Visibility Minimum	
	ft/sec	Mph	d (sec)	D (ft)	y (sec)	Y (ft)	r (sec)	R (ft)
I	88	60	11	968	45	3960	63	5544
	117	80	11	1287	45	5265	63	7371
	147	100	11	1617	45	6615	63	9261
II	206	140	5	1030	21	4526	42	8652
	250	170	5	1250	21	5250	42	10500
	294	200	5	1470	21	6174	42	12348
III	588	400	1.5	882	6	3528	23	13524
	880	600	1.5	1320	6	5280	23	20240
	1176	800	1.5	1771	6	7056	23	27048

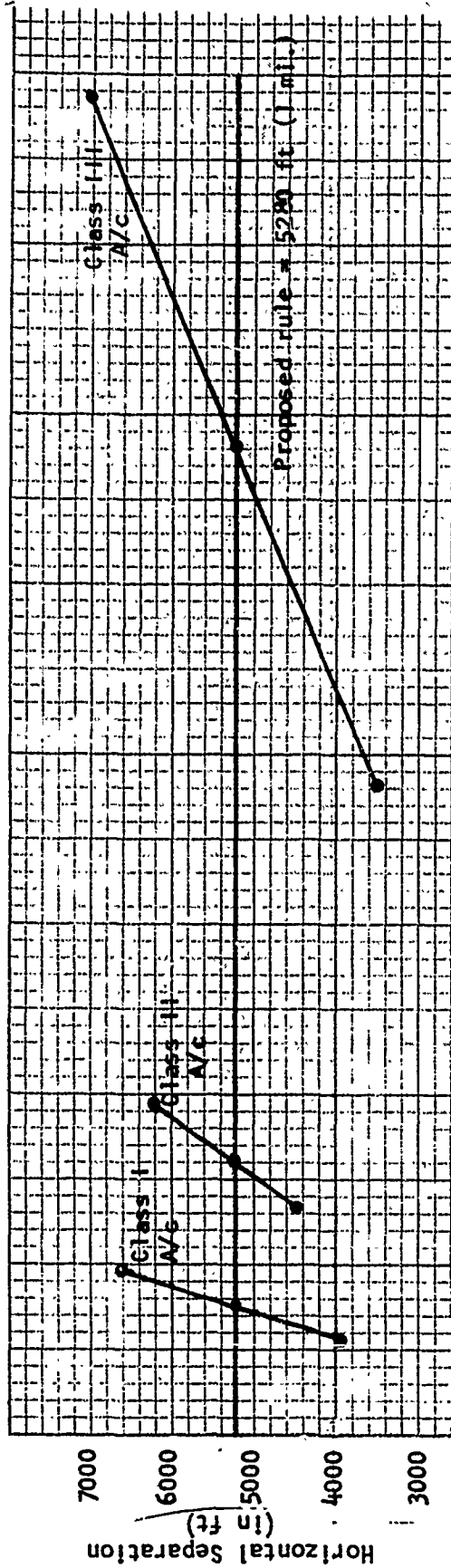


Figure 488. Proposed Horizontal Separation Standard

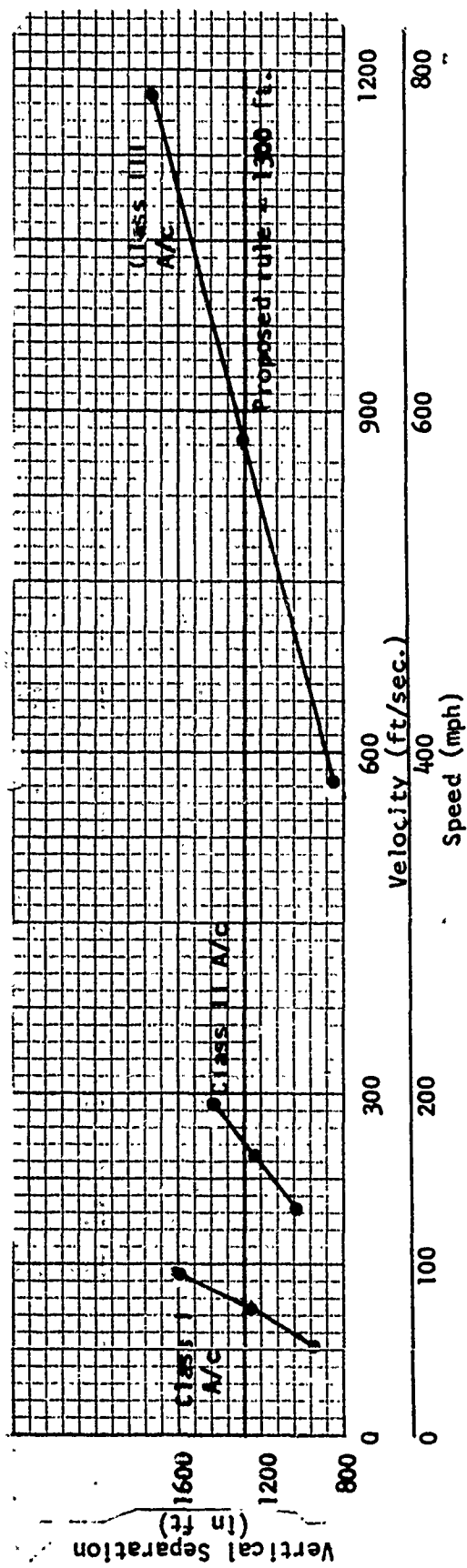


Figure 48A. Proposed Vertical Separation Standard

- d. Not so restrictive that it cuts out too much flying by making conditions too stringent for the protection value received.
- e. Distance should be the same everywhere; no different rules for different times or places, or speeds or headings, etc. since that will lead to confusion or disobedience through lack of knowledge or awareness.

It is believed that the hazard probability computations made herein have led to a set of data which suggest it is reasonable to make a substantial change in the existing vertical distance to cloud separation rule. The data in Table 4 shows the results of the hazard analysis and the display in Figure 48A plots that data. It will be noted that if a vertical standard of 1300 feet is defined (approximately 1/4 mile, which is 1320 feet) that this rule would fall almost exactly on the mean values of each aircraft class which were produced by the hazard analysis described in the previous section. Those mean values are the distances where Class I and Class II aircraft could almost never achieve a near miss (with T=20 seconds) and where the risk from Class III aircraft is acceptably small.

There is reason to be gratified to note that the same separation rule falls almost directly on the mean of each class regardless of speed of the class. In summary, that fact means all aircraft can be subject to the same rule at all times. Simple rules tend to be teachable rules, followable rules, and enforceable rules.

In Figure 48A it is noted that the speed being made good by the aircraft does have some influence on the risk. In part, this is a function of the mathematics involved since the criteria of hazardousness was devised for the mean of the class and hence, as explained above, does not fit so well when that same statistic is arbitrarily used to apply to a different cruising speed. Even so, the results are probably not to be regarded as too bad a fit. The consequences of the misfit are that any aircraft operating at a speed slower than that used to define the mean of its class will receive an extra margin of protection. Any aircraft operating faster than the mean of its class will be operating with something less than its normal margin of protection. In turn, that suggests a simple rule -- slow down around clouds; it can't hurt and it may help. Many aviators have intuitively followed that rule for years.

2. Horizontal Separation Standard (Horizontal Standoff Distance from Cloud)

Since the logic and background of the horizontal separation criterion determination is similar to that just discussed on the vertical standard, the discussion can move directly to study of Table 4 and Figure 48B where the new standoff distance is proposed to be 5280 feet (or 1 mile).

3. Horizontal Visibility Minimum

If the data is plotted from Table 4 into Figure 49, an array of data results which is quite admirably fitted by a very simple visibility rule: flight visibility for an aircraft must equal or exceed 1 mile plus 1/2 mile for each

100 mph of Indicated Air Speed (IAS) or fraction thereof, being made good. Thus, a simple rule guides visibility requirements.

If IAS is:

then the aircraft needs:

0 mph*
1 - 100 mph
101 - 200 mph
201 - 300 mph

1 mile*
1-1/2 miles
2 miles
2-1/2 miles

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Part D - Promulgation of Proposed Separation and Visibility Rules

Based upon the discussion above and after an extensive amount of appropriate discussion and research to be described later herein, the adoption of the following new Visual Flight Rules is advocated. For ease of comparison these have been placed in tabular form directly opposite the text of the existing regulations, as Table 5.

*Obviously, this condition of zero velocity is useless as a practical matter for the figure jumps immediately to 1-1/2 mile visibility as the brakes are released. This number, therefore, has value only as a baseline against which to add further increments of increased visibility as speed is increased.

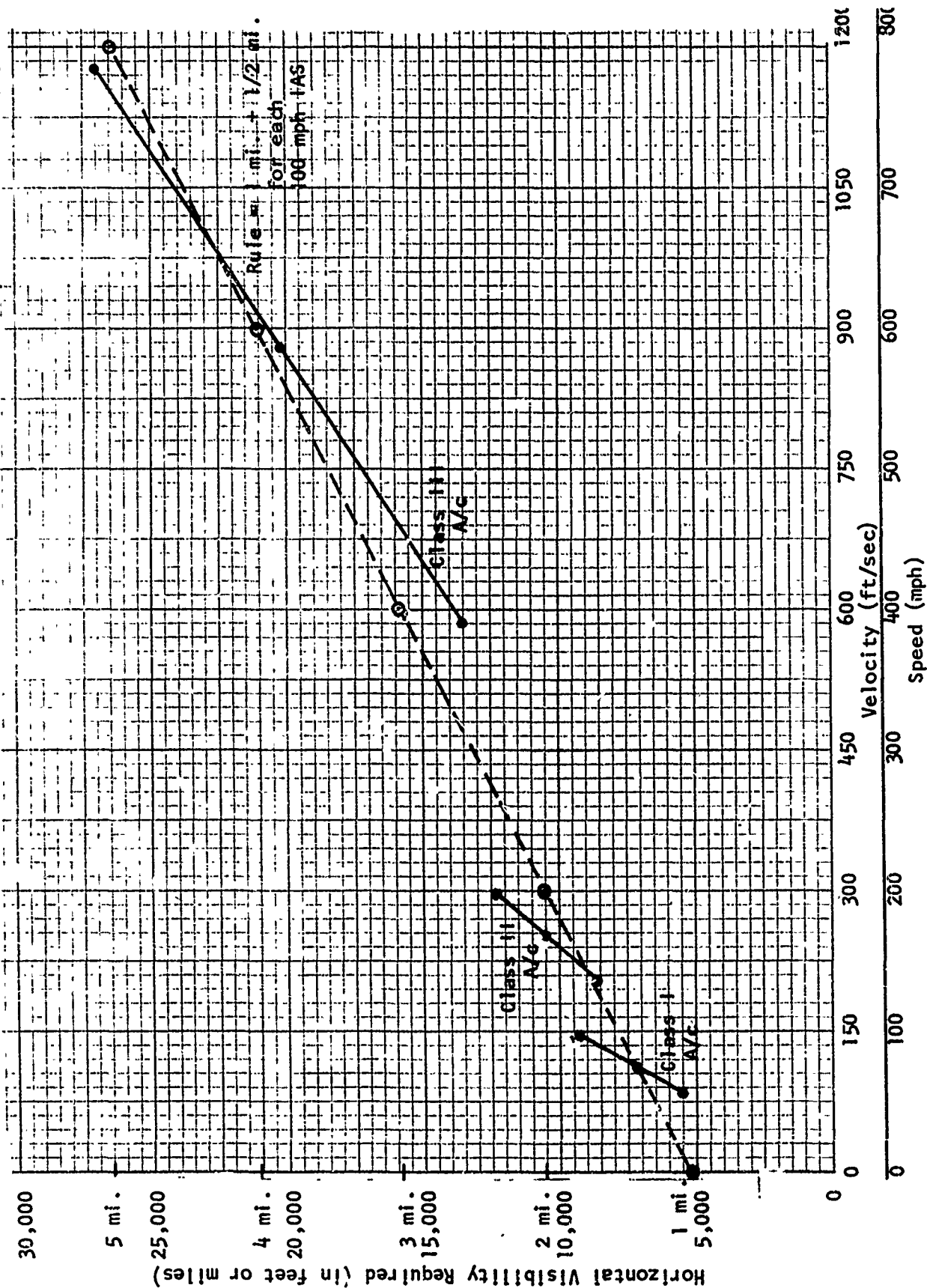


Figure 49. Proposed Visibility Minimum

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES

Existing VFR Rules

91.105 Basic VFR WEATHER MINIMUMS

(a) Distance from clouds. Except as provided in 91.107, no person may operate an aircraft under VFR--

(1) Within the continental control area at a distance less than 1,000 feet vertically and one statute mile horizontally from any cloud formation;

(2) Within any other controlled airspace at a distance less than 500 feet below or 1,000 feet above, and 2,000 feet horizontally from, any cloud formation;

(3) Within a control zone, beneath the ceiling when the ceiling is less than 1,000 feet;

(4) Outside controlled airspace at an altitude of more than 1,200 feet above the surface, at a distance less than 500 feet below or 1,000 feet above, and 2,000 feet horizontally from, any cloud formation; or

(5) Outside controlled airspace at an altitude of 1,200 feet or less above the surface, unless the aircraft is clear of clouds.

Proposed VFR Rules

91.105 Basic VFR WEATHER MINIMUMS

(a) Distance from clouds. Except as provided in Section 91.107, Section 91.79 and Section 121.649 no person may operate an aircraft under VFR--

(1) Within any controlled airspace (control zone, transition area, airway, or continental control area) at a distance less than 1,300 feet (approximately one quarter of one mile) vertically and/or 5,280 feet (one statute mile) horizontally from any cloud formation;

(2) Within a controlled airspace over a congested area, beneath the ceiling when the ceiling is less than 2,300 feet (see Section 91.79);

(3) Within a controlled airspace over other than a congested area, beneath the ceiling when the ceiling is less than 1,800 feet (see Section 91.79);

(4) When outside controlled airspace over terrain of less than 14,500 feet elevation and at an altitude of more than 1,000 feet above the surface or when outside controlled airspace over terrain of 14,500 feet or more at an altitude of more than 1,500 feet above the surface, at a distance less than 1,300 feet vertically and 5,280 feet (one statute mile) horizontally from any cloud formation;

(5) Outside controlled airspace at an altitude of 1,000 feet or less above the surface if the surface is less than 14,500 feet in elevation or 1,500 feet or less above the surface if the surface is 14,500 feet or more in elevation; unless the aircraft is clear of clouds.

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES (Continued)

Existing VFR Rules

91.105 Basic VFR WEATHER MINIMUMS

Proposed VFR Rules

91.105 Basic VFR WEATHER MINIMUMS

- (6) To make a "visual approach" (which is defined as an approach wherein a person on an IFR flight plan is operating in VFR conditions and has ascertained that VFR conditions exist to his destination, has requested and received ATC authorization to deviate from the prescribed instrument approach procedure being utilized and proceed to the airport of destination by reference to the surface) unless the ceiling, flight visibility, and ground visibility meet normal VFR flight requirements defined herein and the pilot shall follow such VFR rules explicitly.
- (7) To make a "circling approach" (which is defined as an approach wherein a person on an IFR flight plan has ascertained that the existing conditions warrant such an approach, has requested and received an ATC authorization to deviate from the prescribed instrument approach procedure being utilized and proceed by reference to the surface to a different runway on the same airport served by the instrument approach procedure which was being followed) unless the ceiling is at least equal to that published in the prescribed instrument approach procedure for a circling approach to the intended landing runway and the aircraft is kept clear of clouds.

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES (Continued)

Existing VFR Rules

91.105 Basic VFR WEATHER MINIMUMS

Proposed VFR Rules

91.105 Basic VFR WEATHER MINIMUMS

- (8) To make a "contact approach" (which is defined as an approach wherein a person on an IFR flight plan has ascertained that the existing conditions warrant such an approach, has requested, and received ATC authorization to deviate from the prescribed instrument approach procedure being utilized and proceed to the airport of destination by reference to the surface) unless the ceiling is 1,000 feet or more, and the aircraft is kept clear of clouds.
- (9) Flight visibility and ground visibility during a "visual approach," "contact approach," or "circling approach" shall equal or exceed that specified by 91.105(b) and 91.105(c) at all times during the approach or landing. In the event one of these kinds of approaches cannot be executed within the limitations imposed by this regulation, the flight shall immediately be returned to instrument flight rules and a standard missed approach procedure shall be executed. These approaches will not be authorized by ATC for airports without a missed approach procedure. These kinds of approaches will not be authorized by ATC when such approaches would require operation over congested areas.

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES (Continued)

<u>Existing VFR Rules</u>	<u>Proposed VFR Rules</u>
<p>(b) Flight visibility. Except as provided in 91.107, no person may operate an aircraft under VFR--</p>	<p>(b) <u>Flight visibility.</u> Except for a helicopter and except as provided in 91.107 and Sec. 121.649, no person may operate an aircraft under VFR (including "contact", "visual", and "circling" approaches) in any airspace (either controlled airspace [control zone, transition zone, airway, or continental control area] or uncontrolled airspace) unless flight visibility in the direction of intended flight and actual flight is at least one statute mile plus one half of one statute mile additional visibility for each one hundred (100) miles per hour or fraction of one hundred (100) miles per hour of indicated air speed being made good at that time. (However, this paragraph does not apply to the operation of a helicopter at or below 1000 feet above the surface at any speed less than 100 miles per hour indicated air speed that allows the pilot adequate opportunity to see any air traffic or other obstruction in time to avoid a collision or effect a safe landing. A helicopter being operated at or above 100 miles per hour indicated air speed shall comply with paragraph (b) with respect to flight visibility.)</p>
<p>(1) in the continental control area unless flight visibility is at least five statute miles; (2) In any other controlled airspace unless flight visibility is at least three statute miles; or (3) Outside controlled airspace, unless flight visibility is at least one statute mile.</p>	<p>(1) [this category subsumed under (b) above] (2) [this category subsumed under (b) above] (3) [this category subsumed under (b) above]</p>

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES (Continued)

Existing VFR Rules

However, subparagraph (3) of this paragraph does not apply to the operation of a helicopter at or below 1,200 feet above the surface at a speed that allows the pilot adequate opportunity to see any air traffic or other obstruction in time to avoid a collision.

- (c) Ground visibility. Except as provided in 91.107, no person may takeoff or land an aircraft, or enter the traffic pattern of an airport, under VFR, within a control zone -

Proposed VFR Rules

- (c) Ground visibility. Except for a helicopter and except as provided in Section 91.107 and Section 121.649, no person may takeoff or land an aircraft or enter the traffic pattern at any airport under VFR unless ground visibility at that airport is one statute mile plus one half of one statute mile additional visibility for each one hundred (100) miles per hour or fraction of one hundred (100) miles per hour of indicated air speed the aircraft will make good within its approach or departure or missed approach from that airport. Approach or departure or missed approach shall be construed to include the period while the aircraft is below 1,000 feet above the surface. (However, paragraph (c) does not apply to the operation of a helicopter at or below 1,000 feet above the surface at any speed less than 100 miles per hour indicated air speed that allows the pilot adequate opportunity to see any air traffic or other obstructions in time to avoid a collision or effect a safe landing. A helicopter being operated at or above 100 miles per hour indicated airspeed shall comply with paragraph (c) with respect to ground visibility.)

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES (Continued)

<u>Existing VFR Rules</u>	<u>Proposed VFR Rules</u>
<p>(1) Unless ground visibility at that airport is at least 3 statute miles; or</p> <p>(2) If ground visibility is not reported at that airport, unless flight visibility during landing, or takeoff, or while operating in the traffic pattern, is at least 3 statute miles.</p> <p>(d) For the purposes of this section, an aircraft operated in accordance with 91.109 at the base altitude of a transition area, a control area, or the continental control area, is considered to be within the airspace directly below that area.</p>	<p>(1) [this category subsumed under (c) above]</p> <p>(2) [this category subsumed under (c) above]</p> <p>(d) For the purposes of this section, an aircraft operated in accordance with Sec. 91.109 at the base altitude of a transition area, a control area, or the continental control area, is considered to be within the airspace directly below that area.</p>

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES (Continued)

Existing VFR Rules

91.107 SPECIAL VFR WEATHER MINIMUMS
IN A CONTROL ZONE

(a) When a person has received an appropriate ATC clearance, the special weather minimums of this section (instead of those contained in 91.105) apply to the operation of an aircraft by that person in a control zone under VFR.

(b) No person may operate an aircraft in a control zone under VFR except clear of clouds.

(c) No person may operate an aircraft (other than a helicopter) in a control zone under VFR unless flight visibility is at least one statute mile.

(d) No person may takeoff or land an aircraft (other than a helicopter) at any airport in a control zone under VFR--

Proposed VFR Rules

91.107 SPECIAL VFR WEATHER MINIMUMS
IN A CONTROL ZONE

(a) When a person has ascertained that the existing conditions warrant a special VFR clearance, has requested and received an appropriate ATC clearance, the special weather minimums of this section (instead of those contained in Section 91.105) apply to the operation of an aircraft by that person in a control zone under VFR. Special VFR clearances will have a clearance limit imposed by ATC which permits them to be used only within the specific control zone for which granted.

(b) No person may operate an aircraft in a control zone under Special VFR except clear of clouds.

(c) No person may operate an aircraft (other than a helicopter) in a control zone under special VFR unless flight visibility in the direction of intended flight and actual flight is at least one statute mile plus one half of one statute mile additional visibility for each one hundred (100) miles per hour or fraction of one hundred (100) miles per hour of indicated air speed being made good at that time while operating under the special VFR clearance. (However, helicopters shall operate under the provisions of Section 91.105(b).)

(d) No person may take off or land an aircraft (other than a helicopter) at any airport in a control zone under Special VFR clearance unless ground visibility at that airport is at least one statute mile plus one half of one statute mile additional visibility for each

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES (Continued)

Existing VFR Rules

Proposed VFR Rules

- (1) Unless ground visibility at that airport is at least 1 statute mile; or
- (2) If ground visibility is not reported at that airport, unless flight visibility during landing or takeoff is at least 1 statute mile.

one hundred (100) miles per hour or fraction of one hundred (100) miles per hour of indicated airspeed which the aircraft will make good during the approach or departure or missed approach while within the control zone.

- (1) [This category subsumed under (d) above]
- (2) [This category subsumed under (d) above]

91.108 SPECIAL VFR WEATHER MINIMUMS OUTSIDE CONTROL ZONES

This regulation does not exist in the old rules.

91.108 SPECIAL VFR WEATHER MINIMUMS OUTSIDE CONTROL ZONES

Special VFR ATC clearances are authorized only for control zones and are not authorized for any other form of controlled airspace (transition zone, airway, or control area) or for uncontrolled airspace.

121.649 TAKEOFF AND LANDING WEATHER MINIMUMS:
VFR: DOMESTIC AIR CARRIERS

- (a) Except as provided in paragraph (b) of this section, regardless of any clearance from ATC, no pilot may takeoff or land an airplane under VFR when the reported ceiling or visibility is less than the following:

121.649 TAKEOFF AND LANDING WEATHER MINIMUMS:
VFR: DOMESTIC AIR CARRIERS ONLY

- (a) Except as provided in paragraph (b) of this section, regardless of any clearance from ATC, no air carrier pilot may takeoff or land an airplane under VFR when the ceiling or visibility is less than the following: 1,000 foot ceiling and one statute mile visibility for each one hundred (100) miles per hour or fraction of one hundred (100) miles per hour of maximum airspeed the aircraft will make good while the aircraft maintains 1,000 feet or less of altitude or leaves the tower control zone if a controlled airport.

TABLE 5. EXISTING AND PROPOSED VISUAL FLIGHT RULES (Continued)

Existing VFR Rules

- (1) For day operations --1,000 foot ceiling and one-mile visibility.
- (2) For night operations--1,000 foot ceiling and two-mile visibility.
- (b) Where a local surface restriction to visibility exists (e.g., smoke, dust, blowing snow or sand) the visibility for day and night operations may be reduced to 1/2 mile, if all turns after takeoff and prior to landing, and all flight beyond one mile from the airport boundary can be accomplished above or outside the area of local surface visibility restriction.

Proposed VFR Rules

- (1) [This category subsumed under (a) above]
- (2) [This category subsumed under (a) above]
- (b) Where a superficial and highly localized restriction to visibility exists either at or near the surface or in a very restricted area of the airspace (e.g., smoke, dust, blowing snow or sand) the visibility required for operations may be reduced to 1/2 mile, if all turns after takeoff and prior to landing and all flight beyond one and one half mile from the airport boundary can be accomplished above or outside the area of local surface visibility restriction.

Part E. Discussion of Proposed New VFR Rules

In Part D, Table 5, sweeping changes have been suggested to the basic VFR rules under which aviation currently operates. The full impact of these changes is extremely complex to consider and, indeed, it is doubtful if any single discussion can cover all the issues. Adequate consideration will probably require a number of lengthy discussions. However, it is felt that an attempt should be made to give at least a partial explanation of what has been done, why it was done, and what the effects of the proposed change would probably be, etc. The present part of the report undertakes this limited discussion.

In the broadest sense, this report has concluded that increased standoff distance from clouds (both vertically and horizontally) plus increased horizontal visibility (both in the air and on the ground) are necessary to improve the safety of operations. Increased visibility per se is not, however, an appropriate thing to seek since the data really has very clearly shown that a *fixed* visibility rule is not so necessary as a rule that relates *visibility* to *velocity*. Many different ways have been tried to put these basic concepts into practice in the rule changes.

A serious effort has been made to *simplify* the rules although, at first, that does not appear to be the case. Examples of the simplification efforts are seen in the suggestion of the same rules for operations in *all* controlled airspace. New 91.105(a) sets a single rule for cloud distance, whereas the old rule had different separations depending upon the type of control zone (old 91.105(a)(1) and old 91.105(a)(2)). Similarly, the new flight visibility rule (new 91.105(b)) is a single rule that combines three varying old rules (old 91.105(b)(1), 91.105(b)(2) and 91.105(b)(3)). The new ground visibility rule (new 91.105(c)) is a single rule that replaces a two-part rule (old 91.105(c)(1) and 91.105(c)(2)).

Further, it is believed that the aviator's job is simplified considerably (as well as being safer) if the *visibility available at that particular time and place is utilized to establish the maximum airspeed at which he can travel. Thus, if the visibility is better airspeed can be increased and if the visibility turns for the worse, airspeed must be decreased.*

It is very important to note that although the rules have seemingly been toughened in certain respects, and it is agreed that this is so in certain instances, the rules have been actually *softened* in a particularly important way. The new visibility rules have made it possible to fly on days with quite poor visibility when, under the old regulations, flight would have been prohibited altogether. Perhaps the greatest single instance of this is in the controlled airspace requirement of 3 miles (old 91.105(b)(2)) which often keeps general aviators on the ground or off the airways. Under the new rule (new 91.105(b)) *if the pilot will simply keep his speed down*, he can move out in 1-1/2 or 2 miles visibility with almost any aircraft that flies. (Maximum permissible speed for 1-1/2-mile visibility would be 100 mph IAS, for 2-mile visibility the maximum airspeed would be 200 mph IAS. Thus, anything up through heavy twin-engined aircraft could go anywhere with 1-1/2-mile visibility and literally anything that flies [including supersonic aircraft] can be held down to 200 mph; so that any airplane made can fly VFR with 2-mile

visibility.) This is a very substantial rule change which should be particularly welcome to the general aviator since it opens many new opportunities to him while forcing the high performance operators to go slowly (so long as they choose to operate VFR). Thus, the speed differential between aircraft is less substantial. At the same time, the rule states that when visibility is good everyone can open up and really move out. It is conceded that this rule imposes some degree of restriction on the high performance aircraft, but they can usually fly IFR if they choose and thus have no speed restriction.

Attention is drawn to the fact that training operations around small, uncontrolled airports are not particularly hindered by this rule. Aircraft can operate in the pattern around these fields largely uninterrupted. Admittedly the new rules require 1/2-mile more visibility, but they also allow 200 feet less ceiling. At the same time, conditions required for VFR operations at controlled airfields are considerably eased.

In general, the lower visibility requirements reflect the observation that increasing numbers of general aviation aircraft and pilots are better equipped to use radio to handle navigation; and that extensive visual views are no longer so necessary for navigational fixes and orientation. The simulation indicates that the distances called out are adequate for collision avoidance.

With the new visibility rules almost everyone can go at an "appropriate" speed, even in some rather poor conditions of horizontal visibility. How fast one goes depends on how well one sees. That seems a desirable state of affairs.

At the same time, the research shows rather clearly that much sterner rules for cloud separation are needed. It is evident that the old rule of "500 feet below cloud" simply will not protect two perfectly innocent aircraft, one flying at 500 feet beneath a cloud deck and the other aircraft (even a fairly slow one) making a normal descent to a landing. As explained at the beginning of this report, vertical altitude change is where most of the "scares" are reported. As a result it is deemed necessary to adopt a much tougher vertical separation rule, and the data was completely consistent in showing that it should be 1,300 feet. It is recognized that this will raise problems with VFR operations at almost all seasons, times, and places.

On a great many days a condition exists with relatively low, closely spaced, altocumulus or stratocumulus cloud with low tops and many small breaks. VFR pilots will want to climb up through the spaces between clouds to the cool clear air with efficient airspeeds that are available only a few thousand feet above. However, since there is insufficient horizontal clearance between clouds they will be doomed to bump along in the crowded airspace beneath the minor barrier of cloud. Low lying stratus decks in winter with beautiful horizontal visibility of over 15 miles beneath them may still not be VFR, and potential VFR aviators are going to be angry to be grounded. Even with a fair ceiling people are going to be stuck in an airport that is surrounded by city (Washington National, Chicago, etc.).

The only possible reply is to point out that if some other aircraft comes storming down out of clouds on an IFR plan (perfectly within rights under present regulations), the research data show that much less than 1/4 mile

vertical separation or 1 mile horizontal separation just is not safe. Instances will doubtless occur in which the requirement for 1,300 feet above cloud will push some VFR pilot above his service ceiling or to an oxygen altitude, especially when coupled with FAR Sec. 91.109 (VFR Cruising Altitude Rules). Since many general aviation aircraft are not suitably equipped, there is bound to be complaint about the impossibility of getting an opportunity to go VFR on-top. With IFR and VFR traffic both growing by leaps and bounds and with more and more traffic choosing to stay with the airways and use the high density terminal areas, the prediction seems secure that the friction between traffic emerging from clouds and traffic operating in the vicinity of clouds will increase. Accordingly, much as it is recognized that to do so will cause extensive disapproval, the 1,300 feet vertical cloud separation, as suggested by the data, is the proposed rule.

Of course, the same thing is going to happen with the 1 mile horizontal cloud separation rule. To all intents and purposes, this rule will probably prevent many VFR climbouts through holes in scattered or broken clouds, since the holes would have to be 2 miles wide to go through legally. There does not seem to be any credible data on the statistical distribution of hole sizes between clouds so that it can only be guessed that they will often be smaller than 2 miles and, therefore, VFR operations above cloud level will often be stymied. If it is desired to have smaller horizontal standoff distances a more lenient standard must be accepted for the frequency of near misses or the IFR traffic must be slowed down. As matters stand, the criteria of the present report are quite clear on 1 mile being the correct figure and, therefore, the data is being adhered to.

But why that ridiculous 2,300 foot ceiling for controlled airspace when the old ceiling was a mere 1,000 feet? The answer, very simply, is that the old 1,000 foot ceiling rule simply has extremely poor chances to protect anyone below that ceiling from IFR dropping down, or VFR traffic zipping down through a hole on top of him. On borderline VFR days the skies are full of aircraft sneaking along the airways, maintaining 500 feet and clear of clouds, trying to find the airport by homing on the same outer marker and ILS the same as the IFR people. The IFR pilot can drop out of the clouds in the approach area and find some VFR aircraft right in his sights. It's all legal but it is also all lethal. What protection can be provided against this?

One way is to raise the VFR ceiling so that it is impossible to get too close to it. Another way is that if a VFR ceiling cannot be obtained, stay clear of controlled airspace or obtain a Special VFR clearance in the areas of greatest IFR mixing hazard (i.e., around major terminals). (This assumes that when under Special VFR someone in ATC will be helping to keep IFR traffic out of the area of known Special VFR traffic.)

At the same time, knowing that many VFR-only qualified aviators would be moving about on days with ceilings below 2,300 feet or 1,800 feet, raising the floor of all controlled airspace except control zones to 1,000 feet above terrain (1,500 feet in mountain areas) is advocated, so that these aviators can still move around. The new rule is even arranged so that all they have to do is adjust their speed to local conditions, stay under 1,000 feet, stay clear of cloud, and stay out of control areas of all types; but still be allowed to come in and out of even major terminal areas by getting

Special VFR for either their first or last few miles around their origins or destinations (unless the origins or destinations are uncontrolled, whereupon they don't have any constraint there either). It is possible to go practically anywhere, almost anytime, with that set of rules; 1,000 feet and 1-1/2 mile and clear of clouds is all that is needed. That certainly doesn't mean that the proposed rules hit the little guy and that he cannot fly. In fact, it allows him considerable freedom to fly under surprisingly adverse conditions. (Perhaps the new rules are even too lenient!) It does mean steering clear of the areas where more cautious, or more technically prepared and equipped aviators usually operate. It means anyone flying over 1,000 feet above terrain (1,500 feet in mountains) has a right to expect everyone else up there will be operating in a rather conservative way. If the weather is good, everyone who is VFR may be expected to be moving around rapidly; if the weather is borderline, everyone who is VFR will be moving around slowly; but in either instance, everyone who is VFR will be very well clear of clouds at above 1,000 feet. It should be quite safe for those above 1,000 feet and those below 1,000 will be slow in speed and sharp in eye.

It is hoped that the modification to the rule on "contact approaches" (new Section 91.105(a) (6) and new Section 91.105(b)) will cause pilots operating on IFR flights to be more cautious about premature cancellation of their plans. It has been suggested that sometimes IFR pilots cancel as soon as they pop out of cloud the first time but they may have difficulty remaining visual underneath, even to the limits required by the "contact" approach. Being unable to get back onto an IFR clearance or IFR procedure readily, they may continue to stumble along quasi-VFR and have near misses with other aircraft that are on VFR plans but who are also encountering the same difficulty in maintaining visual contact, or who are operating under Special VFR. Similar logic prevails in connection with the "circling approach," (new Section 91.105(a) (7) and new Section 91.195(b)). The new rules are generally directed toward raising that standard to make it closer to compatibility with Special VFR and, in uncontrolled airports, to make it safer to mix traffic. Additionally, a specific course of action is indicated in case missed approach becomes necessary. "Contact approaches" are not permitted unless there is a missed approach procedure established.

Questions will be raised, no doubt, as to why changes are suggested in the rules for certain operations around an airport (e.g., circling approaches, contact approaches, etc.,) when the research cited herein has been restricted to the air-to-air collision case exclusively. The answer is quite simple. Both VFR and IFR operations take place at a very large number of uncontrolled airports. Assume operation of an aircraft on an IFR clearance into such a field at the time that field is legally VFR under the proposed new rules. Breaking out of cloud on instrument approach will obviously find a good enough ceiling and visibility to continue as either a visual approach or a circling approach, since VFR operations are already in process. All traffic will have to supply its own traffic separation, however, since there is no tower and the approach controller (if any) or enroute controller is unable to provide traffic separation to the pattern. As is readily apparent, this is an air-to-air detection task. Obviously, the problem is identical to the situation during VFR cross-country and the same visibility requirements should prevail in order to detect an aircraft just becoming airborne off the active runway, an aircraft turning base, or an aircraft popping out of cloud.

Landing aircraft, as everyone knows, have priority over aircraft taking off. It is just as important, therefore, for the pilot of an aircraft which has just completed its run up and is ready to move onto the active runway, to be able to see other aircraft in the pattern or on approach so that he knows not to pull onto the runway at an inopportune time. Thus, whether air-to-air or ground-to-air the same basic visibility rules that this study has described, would appear to be relevant.

The rules stated herein were devised for the air-to-air collision situation and they may, therefore, not be completely relevant to all the situations in VFR aviation operations such as ground visibility and to IFR breakouts to visual, contact, or circling approaches. Further research in these areas is specifically necessary, and the proposed rules are clearly subject to revision.

Sections 91.105(a)(1) and 91.105(a)(2) have been combined to make the same rule for cloud separation within all controlled airspace. After some consideration, no redeeming merit has been found in allowing flight closer to clouds in crowded airspace (controlled airspace, old 91.105(a)(2)) than they could in uncrowded airspace (continental control area, old 91.105(a)(1)). It seems that traffic is probably less dense in the continental airspace or in uncontrolled airspace and it is possible to fly more closely to cloud there. Under the old regulation just the opposite is found; the more dense the traffic the less protection afforded by the rule. The new rule is simplified by making it all the same in all airspace areas, and the separation rule has been made larger for controlled airspace in order to make that more rational.

By the change to Section 91.105(a)(3) the VFR ceiling requirement at controlled airports has been toughened but the safety probabilities of this class of airport have been significantly increased. While recognizing that controlled airports are in a minority, they do handle an enormous amount of traffic, particularly mixed VFR/IFR traffic. In an effort to maintain the quantity of traffic while maintaining safety standards, increased use of the proposed Special VFR around these types of terminals is advocated. Special VFR, even the proposed new version of it, allows a low ceiling and simple clear-of-clouds operation, and it is predicted that restrictions on VFR will be fairly minor and that a great deal more flexibility will be possible than under the 1,000-and-3 rule found in the old 91.105(a)(3) and old 91.105(b)(2).

The flight visibility rule and the ground visibility rule have been made the same (new Section 91.105(b) and new Section 91.105(c)) in order to simplify the rule as well as to reduce the probability of having a mismatch between the two. The similarity of air and ground visibility rules should help reduce at least two conditions that sometimes occur: 1) taking off with fairly good ground visibility only to discover that flight visibility is substantially worse (inversions, industrial smoke, haze, etc.,) so that return to the airport is difficult, if not impossible, and so is continued flight; 2) when flight visibility (horizontal) is pretty good, particularly the view straight down to the ground, but slant visibility very close to the ground, from the altitude of the last 100-150 feet, is quite poor. Many aviators have experienced the situation of making an

overhead pass across the field, seeing everything clearly, and then losing the runway on base or final because of thin low-lying fog or steaming. Having the identical visibility requirements should reduce the likelihood of these two situations occurring.

The new Special VFR (new Section 91.107(b)) still permits operations "clear of clouds" so the pilot can orbit right around the perimeter of a cloud. Seemingly, this violates the intention of increasing the standoff distance to clouds and, in fact, it does. This allowance is made because it is believed that aircraft permitted to make Special VFR should be equipped for satisfactory navigation and communications, and also be equipped with transponders, (described later under proposed additional rule changes). In this way the approach or departure controller could count on knowing where the pilot is. The pilot, being well equipped, would be able to maintain adequate control and position reporting. If unequipped or untrained, no Special VFR clearance would be granted.

It is not considered that the increase in horizontal visibility for Special VFR is unreasonable at all. A great amount of Special VFR Clearances are for operation out of controlled airports situated near major sites of pollution or limited atmospheric interference, so such flights do not usually stay Special VFR very long. Unfortunately, these few miles around the airport are often around major cities and the air is full of antennas, high bridge towers, tall buildings, etc., That is all the more reason to insist on better visibility even if the ceiling is not too good. The rule of relating visibility to speed ought to do the job (new Section 91.107(c)).

There are many other nuances of the proposed new rules and the implications of the differences between them and the old rules, so that this discussion could be carried much further. However, the high points have been made and the way opened to further discussion in other reports or meetings.

The case shall rest in the following open-ended fashion: the new rules are not perfect, but neither are the old ones; the new rules do appear to fit the data of this particular report. If there were more data available, new data, or better data, the rules might more readily be changed. It is hoped that this report will influence changes to be made to existing rules since they are neither perfect nor acceptable as they stand. Some criticism of the findings of this report is expected and if based on data, could be constructive. Constructive criticism on research is what the scientific method is all about. Further discussion will be welcomed.

Part F - New Rules to Study

The VFR rules cannot be contemplated as extensively as this report has done without noting that: 1) some of the VFR rules are inextricably linked with other ATC rules; 2) changes in one set may produce a domino effect in other rules; and 3) changes in other rules might make some of these new VFR rules change. In the present section will be found a very brief account of certain changes which are thought necessary to be given consideration.

1. Base of Controlled Airspace

Change the base of airways or other controlled airspace outside control zones. It is suggested that, except for control zones where control shall extend to the surface, the base of all controlled airspace (transition area, airway, continental control area) shall be 1,000 feet above the surface at elevations less than 14,500 or 1,500 feet above the surface at elevations of 14,500 feet or more. It can be as low as 700 feet now. If changed, the new free space of an additional 300 feet would allow larger maneuvering area for uncontrolled traffic to go about beneath IFR controlled traffic or VFR traffic. Actually, for reasons of giving the low level traffic a bigger area, it would be preferable to have the base raised to 1,200 feet below 14,500 and to 1,700 feet above 14,500. Then, when combined with the 1,300-foot cloud separation rule, ceilings would have to be 2,500 feet and 3,000 feet respectively in controlled airspace (500 less in uncontrolled). That is a very high ceiling to insist upon just so that some people can stumble around in the murk below 1,200 feet and retain their freedom to fly (or keep their freedom to kill themselves and menace the general population). The whole issue is tricky and needs study. Note that in the proposed VFR rule it is already assumed the base of control areas has been raised to 1,000 feet. The question is, should the base have gone a couple of hundred feet higher? That is a question for research and the research should be done before arbitrary adoption of the rules.

2. Speed Restrictions

In the new VFR rule speed restrictions are tacitly and implicitly imposed by saying, in essence "go as fast as you can but don't outrun your visibility." That situation could be helped in another way. Speed restrictions could be imposed as a function of altitude (as FAA has already done below 10,000 feet) but make several strata, e.g., not over 200 below 5,000, not over 300 by 10,000, or over 400 by 14,500 etc. The proposed approach is preferred but the alternative should be given "equal time" and should be researched.

3. Altitude Rate Change Rule

One of the most problematic items in this report is the rule for vertical separation from cloud and, in turn, the impact of that rule on ceiling requirements. That big 1,300-foot rule comes about almost entirely because this research had to assume that emerging aircraft might make rather high rates of ascent or descent. Supposing, instead, that aircraft had to follow another rule which controlled a) their maximum angle of altitude change, or b) some rate of climb/descent: If that angle of climb or descent were kept to 3° instead of up to 10° (as our model allowed) or if rates were 500 feet/minute or less, substantially reduced separation rules could almost be guaranteed (500 - 700 feet) and lower ceilings (1,000 - 1,200 feet), and lower "on-top" altitudes. The present mathematical model will easily evaluate this rule. *It is imperative that this possibility be investigated to its logical conclusion for the potential conclusions are very important to VFR regulations.*

4. Special VFR Equipment and Skill

It is considered here that resort to special VFR flight is a privilege and not a right, although this viewpoint will, no doubt, be questioned. In return for this privilege, and since those who exercise it operate their aircraft under conditions which have an enhanced likelihood of causing substantial havoc to the public, it seems reasonable to insist that those who request Special VFR clearances should possess and be able to utilize certain minimum equipment. As a minimum, it is speculated that the pilot shall have and shall be able to use proficiently, appropriate radio navigational equipment (VOR, ADF, and/or ILS), a two-way radio communications link in constant ATC contact and listening watch, and a functional transponder. These things are reasonable and proper. They are designed to fill two purposes: 1) to make sure the pilot can go where he is told to go (or if he cannot get there because of adverse weather not knowable to the controller, he can inform ATC immediately and precisely where he is at all times), and 2) to provide ATC with positional information. This constant communications, navigation, and location data is judged to be necessary because there is a strong likelihood of IFR traffic under positive control in the area at the same time, and ATC has an iron-clad contract to provide separation to the IFR pilot who cannot provide his own. The only sure way to do that is to have firm knowledge of the activities of the Special VFR aircraft. There are numerous researchable aspects to this problem.

5. Special VFR Climb and Descent Rule

The new horizontal cloud separation rule, tentatively proposed herein, will often make it very difficult for a VFR aircraft to move up and down through open spaces between or breaks in clouds. In many areas of the airspace a new ATC service could be provided to help pilots go through these holes with the assistance of ATC. A suitably equipped aircraft (see paragraph 4 above) would simply call ATC and ask for help in penetrating the cloud layer. If workload and IFR traffic load permit, ATC would monitor the penetration and warn of the presence of other aircraft. For his part, the pilot would maintain control of his aircraft solely by visual reference, making sure to remain clear of clouds (where he would be forced onto instruments for which he is neither cleared nor qualified), and be obliged to accept instructions designed to maximize his separation from IFR traffic and other known VFR traffic. Service would be rendered only during the penetration period except as such a penetration might also be tied together with Special VFR services in a terminal area too (as from "departure" "on-top" or from "on-top" to "runway-in-view") in case of arrival or departure. Like IFR service, ATC should retain the right of refusal or deferral of service and Special VFR service should take second priority behind IFR. Special VFR penetrations would not be permitted without positive ATC clearance. Having such a service might go a long way toward taking the sting out of the otherwise harsh horizontal clearance from cloud rule.

Each of the rule changes above should, for various reasons, help the VFR rule but before adoption is seriously considered they should be studied very intensively to ascertain their utility, practicality and effects.

Part G - Further Research to Help the VFR Rules

As one final explanation, the highly controversial nature of the proposed new rules is fully comprehended. Reduced to basics, the grounds for the argument center on three fundamental issues:

- a. Opinions legitimately differ on what is "safe;"
- b. Substantial areas exist wherein sufficient hard data is not available to permit other than speculative statements;
- c. The simulation on which the proposed rules are based was very, very limited. Under the necessity for economy and speed it was necessary to adopt a number of restrictive and limiting assumptions which have been explained in the text.

Under such conditions, and considering the limited scope of the present work, it is small wonder that there should be widespread opportunity for disagreement.

With respect to the issue of "what is safe" it is realized that the mathematical analysis is much too rigorous: 1) the model assumes the two aircraft within reasonable striking distance of each other on every run when, in reality, they are generally so far apart that the conditions simply do not occur very often for two aircraft to make runs on each other; 2) rather severe near miss conditions (234-528 feet) have been set up which are fairly definitely "close"; 3) rather severe criteria have been set for safety (roughly, that slow aircraft could almost never have a near miss and fast aircraft would very infrequently do so). Perhaps a more lenient criterion is in order especially since, in view of 1) above, the aircraft seldom confront each other in the first case; and 4) it must be remembered that a near miss is, after all, not the same as a hit. According to the model airplanes could come that close to each other many times with very little likelihood of collision.

When the situation is analyzed, it is something of a wonder that aircraft every collide even under today's rules. But they do, and hence our decision to go for generally tougher rules.

All the conditions described above combine to suggest that this report may have leaned too far in the direction of playing it safe. Perhaps it would be better to relax the rules somewhat and become resigned to scaring each other more often than the proposed rules would allow, killing each other only very infrequently but retaining substantial operational freedom in return. The FAA needs data on how much risk the public will accept. That data, in turn, would go far to define how to set separation standards. This simulation cannot do it all.

So much for the discussion of what are acceptable limits for safety. Next will be discussed why it has been impossible to do a better job, i.e., the lack of data in certain areas.

No one appears to know, but it is necessary to know such things as the following in order to do a satisfactory job of modeling:

- a. The separation between clouds;
- b. How big clouds are;
- c. Distributive statistics for clouds (what per cent of time are they 8,000 feet high? Where are clouds found? ...)
- d. What is the cost of being grounded;
- e. How rapidly do pilots actually cause their aircraft to climb, descend, turn;
- f. What is human search behavior (time, pattern, etc.);
- g. What is typical human reaction time in air-to-air confrontations;
- h. What is typical aircraft reaction time;
- i. How well can aviators estimate vertical separation from the ground; vertical distance from clouds; separation from other aircraft; horizontal distance from clouds; horizontal visibility with or without other visual landmarks;
- j. etc.

By now it can be seen why the recommendations are submitted with some trepidation. There are an enormous number of things which are simply not known about the conditions of collision geometry and, equally important, very many things are not known about the cost/benefit aspects of the model. Lacking good information on these kinds of issues only a partial model can be developed and the proposed regulations passed on as grossly incomplete data. There is some apprehension and disquiet about the conditions in which this report is concluded but it is the best that can be done under existing restraints.

Further research is, most assuredly, in order.

SECTION VII. SUMMARY

In the study reported herein, a methodology has been developed and used to generate a numerical safety rating scheme for quantifying the degree of hazard associated with aircraft-to-cloud separation minimums and with speed-visibility restrictions. The methodology is based on theoretical considerations of the near-miss geometry and the probabilistic nature of hazardous conditions existing.

The geometrical analysis is basically a three-dimensional vector analysis of a two-aircraft near miss geometry, basing the projection of aircraft flight trajectories on the assumption of straight line, unaccelerated flight trajectories. One aircraft, the reference aircraft, is assumed flying straight and level at a constant velocity; the other, designated the emerging aircraft, is allowed certain constant relative position, velocity, and heading with respect to the reference aircraft. A quadratic equation in time is developed in which the three constants of the equation are functions of the geometrical parameters: relative velocity; relative heading, near miss distance; and initial relative position of the two aircraft. A hazardous near miss is inferred to exist when the geometrical parameters of the two aircraft predict the passage of one aircraft within a near miss distance, M , of the other, and within a critical reaction time, T . Predicted close passages in a time greater than T are considered safe since the pilots are assumed to have adequate time to detect, evaluate, and react to the threat at hand. Mathematically, the hazardous near miss conditions exist when the proper combination of geometrical parameters is selected such that the roots of the quadratic equation are real and at least one root is greater than zero and less than T .

A set of numerical degree-of-hazard functions are generated by first defining the conditional probability of a hazardous near-miss occurring given the initial position of the emerging aircraft with respect to the reference aircraft. This probability is evaluated as the ratio of emerging aircraft flight path angles, Γ , and relative headings, ψ , which mathematically satisfy the hazardous near-miss conditions to the range of ψ and Γ allowable. The conditional probability, $P_{H/p}(\epsilon, \delta, r)$ is a function of the relative velocity, K , and the initial position coordinates of the emerging aircraft; ϵ , δ , and r , where ϵ and δ are the elevation and bearing angles respectively and r is the range from the reference aircraft. Defining $P_{H/p}(\epsilon, \delta, r)$ as a simple ratio assumes all heading and flight path angles are equally likely. In this analysis a full range of 360° for ψ is allowed and Γ is limited to $\pm 10^\circ$.

The degree of hazard functions are developed for each of the three separation requirements to be determined: the vertical and lateral separation distances from cloud boundaries and the radial (horizontal) visibility limits.

The degree of hazard functions are defined as the spatial integrals of the conditional probability function over the appropriate surface or linear dimensions. The integration surfaces and lines surrounding the reference aircraft represent the cloud boundary surfaces or visibility limits, every point along which an emerging aircraft is assumed to appear. The integration

of $P_{H/P}(\epsilon, \delta, r)$ assigns a value to the degree to which a cloud or visibility boundary at a given separation distance presents hazardous conditions to the pilot of the reference aircraft. An hazard function of zero is the safest. The dangerousness of a given separation standard increases as the value of the respective hazard function increases. The actual numerical values of the hazard function developed herein hold no probabilistic significance.

The degree of hazard functions for encounters between three different velocity classes of aircraft are computed using a digital computer. The three aircraft classes represented are: a low-speed (80 mph) single-engine light aircraft; a medium speed (200 mph) General Aviation aircraft or other aircraft under air terminal area velocity limitations; and a high-speed (600 mph) jet. The first two classes comprise the majority of operating aircraft and the outcome of encounters between these aircraft are weighted more heavily than encounters with the high-speed aircraft. In all cases involving the first two aircraft classes the degree of hazard functions show a relatively sharp drop off to zero in hazard as cloud separation requirements are increased. Encounters by any class with the high-speed aircraft show an initial sharp drop in the hazard functions followed by a long gradual sloping off to zero. On this basis, the best vertical and lateral aircraft-to-ground separation standards and the visibility minimums for a given class of reference aircraft are defined to be the point at which encounters with the first two classes of aircraft go to zero or very nearly so. The residual hazards of encounters with high-speed aircraft are assumed to be diminished to an acceptable level by the infrequency of such encounters. For both the lateral and vertical cloud separation requirements the best separation distances are found to be nearly equal distances for all aircraft classes; therefore, single distance requirements can be chosen for all aircraft. The best choices for horizontal visibility standards are found to vary with the speed of the reference aircraft, therefore, visibility minimums are selected on a speed-dependent basis.

Although it is a gross oversimplification to state them so starkly, the proposed new VFR rules may be abstracted to the following:

- a. Vertical separation above and below clouds = 1300 feet (1/4 statute mile)
- b. Horizontal separation from clouds = 5280 feet (1 statute mile)
- c. Visibility = 1 statute mile plus 1/2 mile for each 100 mph of Indicated Air Speed.

The report notes numerous difficulties in using an oversimplified, computerized mathematical model to derive the proposed new rules, especially when many of the input terms for the model are based upon inadequate data. Numerous suggestions are made for research to obtain suitable data which would, in turn, improve the value of the model and, hence, the VFR rules.

Specific caution is made against adoption of the proposed new VFR rules as is. A period of extensive analysis and study, including considerable discussion and substantial validating research is most assuredly warranted.

Meanwhile, admitting the numerous inadequacies of the study, it is nonetheless put forth with considerable pride and confidence that this report offers a quite innovative piece of research and, more importantly, offers a rallying point for the subsequent discussion and research which is anticipated and needed.

APPENDIX A. COMPUTER PROGRAM

AVSTXY - EFN SOURCE STATEMENT - IFN(S) - 12/22/69

```

INTEGER PROB (200), CC
REAL K, M, M2, K21, K22, S(4501)
DATA RDC /57.29578
1 FORMAT ( 8F9.0)
2 FORMAT (36HOPROBABILITY INTEGRAL OVER X-Y PLANE F15.2)
3 FORMAT (4H1D = F10.2, 4H M = F10.2, 4H K = F10.2,
* 4H X = F10.2, 3H TO F10.2, 3H BY F8.2,
* 4H Y = F10.2, 3H TO F10.2, 3H BY F8.2 )
4 FORMAT (2F15.5)
5 FORMAT ( 1X 3214 )
110 = 50
101 = 110 / 5
DEN = ( ( 200 / 101 ) + 1 ) * ( ( 3600/110 ) + 1 )
DO 100 I = 1, 901
100 S(I) = SIN (FLOAT (I-1) / (10. * RDC) )
DO 104 I = 1, 900
11802 = 1802 - I
13602 = 3602 - I
S(11802) = S(I)
S(1+1801)=-S(I)
S(13602)=-S(I)
104 S(1+3601)= S(I)
1000 READ (5,1) D, M, K, X, HX, XSP, YST, YSP
ACCUM = 0.
HY = HX
WRITE(6, 3) D, M, K, X, XSP, HX, YST, YSP, HY
IF ( D .LE. M ) IE = 3701
IF ( D .GT. M ) IE = 3601
M2 = M * M
K21 = K * K + 1.
K22 = K + K
DK = D * K
D2 = D * D
101 Y = YST
11 = 0
X2 D2 = X * X + D2
102 CC = 0
R2 = Y * Y + X2 D2
C = R2 - M2
IF ( C ) 108, 108, 111
108 11 = 11 + 1
PROB (11)= DEN
GO TO 113
111 IGS = 3500
105 IGC = IGS - 2700
SIGS = S(IGS)
SIGC = S(IGC)
CGK = K * SIGC
CG2K = -K22 * SIGC

```

```

IPS      = 1
103 IPC   = IPS + 900
SIPS     = S(IPS)
SIPC     = S(IPC)
B        = 2. * ( CGK*(X*SIPC + Y*SIPS) - X + DK * SIGS )
IF ( B   )          109, 106, 106
109 A     = K2I + CG2K * SIPC
DTRMNT   = B*B - 4.*A*C
IF ( DTRMNT )      106, 110, 110
110 AA    = 40. * A
BB        = ABS(B)
IF ( BB .LE. AA )   GO TO 107
BBAA     = BB - AA
IF ( DTRMNT .LT. BBAA*BBAA ) GO TO 106
107 CC    = CC + 1
106 IPS    = IPS + 110
IF ( IPS .LE. 3600 ) GO TO 103
IGS      = IGS + 101
IF ( IGS .LE. 1E )   GO TO 105
II       = II + 1
PROB(II) = CC
FC       = CC
ACCUM    = ACCUM + FC / DEN
113 Y     = Y + HY
IF ( Y .LE. YSP )   GO TO 102
WRITE ( 6, 5 ) ( PROB (I), I= 1, II )
X        = X + HX
IF ( X .LE. XSP )   GO TO 101
WRITE (6, 2) ACCUM
GO TO 1000
END

```

APPENDIX B. GLOSSARY

The following is a list of terms used throughout the report, together with definitions of those terms:

- d = (Variously used.) Separation distance, in seconds, between the reference aircraft and the emerging aircraft. Same uses as "D" (which see). See also H_V , H_L , and H_H .
- D = (Variously used.) In all uses the concept is that of distance between the reference aircraft and some hypothetical distance or geometric plane: 1) separation distance, in feet, between plane of the reference aircraft and the plane on which the emerging aircraft first appears. Therefore, the vertical distance between the planes of the two aircraft at the start of the confrontation; 2) used to represent vertical distances from cloud as if the reference aircraft was various distances away from cloud base or cloud tops; 3) standoff distances horizontally from cloud; or 4) limits of horizontal visibility.
- Emerging aircraft = An aircraft assumed to appear from any proscribed direction at any proscribed distance and operated in such a way as to challenge the reference aircraft. Said to be "emerging" because it may appear out of clouds, from behind clouds, or out of poor longitudinal visibility conditions. Sometimes called the "obscured" aircraft.
- H_L = Lateral Hazard. A vertically oriented plane lying perpendicular to the y-axis of the reference aircraft, parallel to the x-axis of the reference aircraft, and representing the lateral separation (the horizontal separation) from the side of a cloud. This plane can be located at various distances to represent various degrees of hazard. The distance, d , between these planes is the separation distance which will achieve certain various probabilities of near misses given certain other definable circumstances.
- H_H = Horizontal (Radial) Hazard. The probability of a near miss occurring from a point on the perimeter of a coplanar horizontal circle surrounding the reference aircraft. The distance, d , between the location of the reference aircraft and the location of the emerging aircraft is the separation distance which will achieve certain various probabilities of near misses within time, t , given certain other definable circumstances.

H _v	= Vertical Hazard. A horizontal plane lying perpendicular to the z-axis of the reference aircraft, parallel to the x and y axis of the reference axis and representing cloud base or cloud top. This plane can be located at various distances to represent various degrees of hazard. The distance, d, between these planes is the separation distance which will achieve certain various probabilities of near misses given certain other definable circumstances.
IFR	= Instrument Flight Rules. Control of flight by reference to instruments and without sufficient visual data from the environment to control the aircraft or detect other aircraft. One can operate IFR under VFR conditions but not conversely. IFR flights are to maintain visual surveillance whenever clear of cloud.
k	= The ratio of the emerging aircraft airspeed to the reference aircraft airspeed.
m	= miss distance expressed as time in seconds between the aircraft.
M	= 1) magnitude of near-miss distance in feet; 2) size of the near-miss sphere in feet.
Near-miss sphere	= An hypothetical space of certain radius which surrounds and moves with the reference aircraft. Contact with the surface of this sphere (or incursions into it) by the emerging aircraft constitutes a near-miss. Theoretically, passage of the emerging aircraft through the center of the sphere would constitute a collision
r	= Range between the emerging aircraft and the reference aircraft expressed as time in seconds.
R	= Slant range, in feet, between the emerging aircraft and the reference aircraft.
Reference aircraft	= a) the aircraft against which an emerging aircraft is contending; b) own aircraft; c) protected aircraft.
S	= Surface of a horizontal plane from which the emerging aircraft enters the confrontation.
See-and-avoid	= VFR flight.
See-and-be-seen	= VFR flight.
T (or t)	= Time.

v	= Velocity
VFR	= Visual Flight Rules - control of flight and collision avoidance through recourse to visual surveillance of the environment.
VFR On Top	= At the present time, control of flight and collision avoidance by visual means while operating 1,000 feet or more above clouds.
x-axis	= Longitudinal axis (heading) of the reference aircraft.
y-axis	= Transverse axis of the reference aircraft. Together with the x-axis defines the horizontal plane on which the reference aircraft operates parallel to the surface of the earth, the base of clouds, or the tops of clouds.
z-axis	= Perpendicular axis of the reference aircraft. Defines the vertical plane (or altitude plane) to the earth (as absolute altitude), to the emerging aircraft (as relative altitude), between earth and cloud base (as ceiling), between reference aircraft and cloud (as distance above or below cloud).
Γ	= Flight path angle, in degrees, of ascending or descending aircraft. (The emerging aircraft is the only one assumed to climb or descend herein.) May be thought of as angle of altitude change but not as rate of climb, though that measure is related.
δ	= The relative bearing angle of the emerging aircraft from the reference aircraft.
ϵ	= The relative elevation angle of emerging aircraft with respect to the reference aircraft.
θ	= The relative azimuth angle from which a near-miss is achieved. Measured from heading of reference aircraft.
ϕ	= The relative elevation angle from which a near-miss is achieved. Measured from horizontal plane through the reference aircraft.
ψ	= The relative heading of the emerging aircraft with respect to the reference aircraft.

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